MAURITIUS RESEARCH COUNCIL

FUZZY CONTROL OF BATCH DYEING PROCESS

Final Report

August 2003

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Batch Dyeing Process

FINAL REPORT

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ABSTRACT

The control of dyebath pH in the dyeing of cotton with reactive dyes is critical for batch to batch shade reproducibility, levelness of dyeing and the optimisation of the dyeing process. Conventional controllers have not proved too successful in controlling dyebath pH since it is very difficult to develop a mathematical model for the dyeing process. The relationship between various parameters of dyeing is highly complex, non-linear and exhibits time-varying behaviour.

One method to deal with such complex situation is to apply fuzzy control to the dyeing process. Fuzzy control is a modern control method that uses a control algorithm based on human reasoning to take control decisions. In this project work, a fuzzy control system was developed to monitor the pH of the dyebath during the dyeing process. An on-line pH meter and dosing pumps were mounted on a laboratory jet dyeing machine. Various preset pH profiles were used to study the tracking performances of the control system.

Simulation and initial experimental results of the system performance proved to be very promising. Further fine-tuning of the system gave very satisfactory tracking performances of the dyebath pH up to pH values of around10.0. Above pH 10.0, the tracking performance degrades.

With respect to the dyeing performance, the controller did not significantly improve the colour yield of the dyed fabric. However, results showed a high degree of shade reproducibility between dyed batches when using the proposed controller for the applied preset pH profiles.

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CHAPTER 1

INTRODUCTION

Reactive dyes have been the most active classes of textile colorant over the last two decades; the interest in these dyes being demonstrated by the large number of patents and publications recorded in the late 1980's [1]. The success of reactive dyes has been mainly attributed to their unique ability to bond covalently with the substrate during application. These dyes are predominantly applied to cellulose, especially cotton which is by far one of the most popular textile fibre, for their brilliance and range of hues and they offer excellent wet fastness and moderate to high light fastness. They may also be applied to wool, nylon and silk.

In Mauritius, the most important material processed in dyehouses is cotton; either in the form of yarn or fabric and it constitutes more than 90% of the wet processing activity and about 55% of dyestuffs used are reactive dyes [2].

However, reactive dyes on cellulose have certain technical limitations. One of the major problems is the low to moderate exhaustion and fixation levels under alkaline conditions. Such colour loss has become increasingly unacceptable both economically and environmentally. A number of works have been carried out, over the past decades to develop and improve the dye in this respect [3, 4].

Besides, the control of key process parameters such as dye concentration, temperature and dyebath pH are critical for better dye exhaustion and fixation, level and on-shade dyeing, easier washing-off after dyeing and batch to batch shade reproducibility. The successful dyeing of cotton with reactive dyes is very dependent on pH and so its control is very important during the dyeing process. The control of temperature on modern dyeing equipment is quite satisfactory with the use of sophisticated and robust temperature sensors, efficient heat exchangers and reliable temperature controllers. The increasing application of computer control in dyehouses with automated dispensing and dosing of dyes, chemicals and auxiliaries provide dyers with a better control of dyebath concentration and liquor volume.

During dyeing, however, the control of pH is quite complex and difficult since it has been shown that pH varies, to different extent, with dyeing parameters such as temperature, salt concentration, the quality of the cotton fabric, the water quality and the presence of dyes and auxiliaries. The interaction is non-linear and it is very difficult to create an accurate mathematical model to control pH by conventional means. In this respect fuzzy controllers are very promising and they have been successfully applied in various other systems [5,6].

Several workers are investigating the use of different fuzzy logic control systems that combine various control parameters during dyeing to achieve optimum exhaustion level and rate, levelness and shade reproducibility of batches for any dye-fibre system. The benefits of such systems are enormous and certainly justify further investigation [7, 8].

1.1 Literature Review

Several researchers studied methods of incorporating closed loop feedback control of dyeing parameters into the automatic control of dyeing machinery [5, 8]. One method was based on the use of preset pH profiles that were linear, exponential, or quadratic in shape. An online pH meter and dosing pumps attached to a pilot-scale dyeing machine were used together with mathematical models that describe the conditions of the dye liquor at any given time. Other factors like temperature, electrolyte concentration, dye and other additives in the dyebath were studied for inclusion in the model. The results based on experiments demonstrated a relatively high degree of accuracy and reliability of pH control either according to preset dosing or to preset pH change profiles [5].

The same workers studied another method of process control based on the application of feedforward preset exhaustion profiles. The control process consisted of a comparison between a dynamic variable such as pH or dye concentration and a set value and an action was required to bring the measured value to the set point value [7].

In [8], two dyebath monitoring systems were developed, one of which is a dyebath data acquisition system that acquires pH, conductivity, temperature and absorbance data in real time. It has been used to model and optimise some exhaust dyeing parameters. Other researchers have developed a control strategy for package dyeing based on a linear build-up in dye deposition error which is the difference in the amount of dye deposited on the inside and the outside of the package and is related to a visual colour difference. The control strategy was successfully implemented by means of an in-line measurement of dye liquor concentration and feedback control of liquor temperature to achieve and maintain the desired rate of exhaustion using different dye addition profiles [9].

Other work in the field of dyebath pH control was carried out [10] where a self-tuning proportional-integrated-derivative (PID) pH controller was proposed, with the ability to auto-tune the gains by an estimated parameterised model which is updated by input and output sequences. They initially realised that with a fixed gain PID controller it was difficult to manage non-linear and time-varying pH systems and which were difficult to model. The developed controller was applied to a simplified dyeing process that was simulated and the results showed that the controller could bring the pH from any initial value to any other value for the dyeing process and demonstrated self-tuning ability.

The same authors later developed a fuzzy gain-scheduled PID controller to monitor and control dyebath pH for a simplified dyeing process. The results showed that under conditions that may constantly cause the pH to deviate from the set value, the controller could maintain the pH at the set values by tracking down the changes in set values [11].

Work carried out during a small laboratory scale experiment of direct dyes onto cotton fabric showed that fuzzy control could effectively be used to deal with complex control process such as the control of dye concentration, pH and temperature at the desired values during dyeing [6].

1.2 Problem Definition

Any dyeing process involves three major components; the dye, the substrate and the process. In cotton reactive dyeing, the dyes are popular for their very desirable characteristics [3] but quite notorious in environmental terms since the degree of fixation of the dye onto the substrate is, in many cases, not very satisfactory. A lot of efforts have, therefore, been carried out the past two decades in order to improve the performances of reactive dyes onto cotton substrate [12, 13, 14].

There has also been much work carried out in the area of the cotton substrate [15] in order to make it more receptive to the dye under less alkaline condition, since much of the dye is hydrolysed at high pH values. With regard to process improvement, there have been developments in recipes and a greater understanding of process parameters [12, 16, 17, 18].

Although process control with respect to the control of dyebath pH, which is very critical in the dyeing of cotton with reactive dyes, has started some time ago the situation is not always satisfactory. Conventional controllers such as PID controllers have not proved too successful in controlling the pH of dyebaths since it is very difficult to model the dyeing process whereby dyebath pH parameter exhibits strong non-linearity and time-varying behaviour. It is, therefore, proposed to use fuzzy logic control system to monitor and control dyebath pH, one of the most sensitive parameter of the dyeing process.

All these works are being carried out with a view to improving the colour yield and reducing the amount of dye in the wastewater, improving the shade reproducibility and the level of right-first-time production and the quality of the dyeing.

1.3 Reactive Dyes

A reactive dye is defined as a coloured compound, which has suitable groups capable of forming covalent bonds between the dye and the fibre. Reactive dyes are based on a chemical reaction between the dye and the fibre. Cellulose behaves as a polyhydric alcohol and most reactive dyes react with cellulose under alkaline conditions through either nucleophilic substitution or addition reaction [19].

1.3.1 History of Reactive Dyes

In recent years, cotton as a textile material has been increasingly consumed because of its excellent fibre properties. Consequently, reactive dye, being one of the dyestuffs for cellulosic fibre, has also been increasingly used each year because of its brilliant shade, excellent wet fastness properties and wide range of application [20].

In 1925, a 20 derivatives of isatoic acid anhydrade were found to react with cellulose under mild conditions in presence of sodium carbonate and in 1952, it was clear that cellulose fibres could be dyed with reactive dyes from an aqueous dyebath in the presence of alkali which is necessary for fixation.

The first range of these dyes, the Procion MX (ICI) and Cibacron (CGY) dyes, were introduced in 1956 and were followed by the Procion H, Remazol (HOE), Levafix (BAY), Primazin (BASF), Drimarene (S) and other ranges. An essential feature of every member of each of these groups of dyes is the presence within the molecules of an atom or group that can react covalently with the hydroxyl, or more strictly the ionised hydroxyl groups in cellulose molecule. The group of atom in the dye that reacts covalently with the fibre is known as the functional group of the dyestuff [20].

1.3.2 Features of Reactive Dyes

For convenience, a reactive dye may be represented as follows:

S — D — B — Y — X

Where D is the dye containing the chromophore. The chromophore is usually an azo or anthraquinone group.

B is the bridging group although this may in many cases be part of the chromophore.

Y is the unit carrying the reactive group.

X is the leaving group

S are solubilising groups

1.3.3 Mechanism of Reactive Dyes onto Cellulose

Reactive dyes may be applied using batch exhaustion, semi-continuous and continuous methods and by printing techniques. Under neutral conditions, it has been shown that the reaction between the dye and the fibre is ionic in character. The dye is substantive to the substrate and therefore the reactive dyes are transferred from the dyebath to the fibre due to physical forces of attraction. The dyes then diffuse into the cellulose as would direct dye into the fibre. They are however unable to react with cellulose as the concentration of cellulosate ion is extremely low under that condition. Addition of alkali causes ionic concentration to increase and reaction occurs with the formation of covalent bonds between the dye and the fibre. The chemical reaction proceeds either through nucleophilic addition or substitution reaction depending on the nature of the reactive group of the dye.

In dyeing of cellulose with reactive dyes, the dye-fibre reaction is almost always promoted by alkaline conditions, as it is also the reaction of the dye with the water (hydrolysis), which gives a non-reactive dye (hydrolysed dye). Promoting dye-fibre combination and suppressing the reaction with water increases the efficiency (fixation) of the dyeing process. Indeed, the wet fastness of the dyeing depends on this. The development of maximum fastness to wet treatments, however is also dependent on the complete removal from the fibre of dye not chemically bound to it. In addition, certain dyed cotton fabrics are sensitive to either acid or alkaline hydrolysis after the dye has reacted with the fibre and this results in breaking down of dye-fibre bond giving inferior wet fastness.

1.3.4 Application Conditions of Reactive Dyes onto Cotton

The pH of the Dyebath

The pH of a solution is a measure of the concentration of hydrogen ion, $[H^+]$, in solution. The p comes from power and H from the element hydrogen. It defines the acidity or alkalinity of the solution. The definition of pH is given in Equation1 [5].

$$\mathbf{pH = -log_{10}[H^+]} \qquad \textbf{Eq. 1}$$

The pH profile of the dyeing process for fixing reactive dye onto cotton depends on the individual dye, the temperature and the time of dyeing. Normally, the pH decreases with increase in temperature and time of dyeing. At high pH values (alkaline) the dyes are hydrolysed and can no longer react with the fibre. This results in poor colour yield due to loss of dye and poor wet fastness. Dyeing should be therefore start at low pH (7-8) so that the dye molecules are not hydrolysed or fixed on the fabric as it enters in contact with it. The common practice is to have the pH more or less constant initially over a certain period of time to allow the dye to enter the fibre before it gradually increases from 8 to 11 as the process continues. This results in a relatively good dyeing. pH profiles could be a linear, quadratic or exponential depending on the nature of the dyeing and there may be other possible profiles that could give more satisfactory dyeing results in terms of exhaustion and fixation levels and these are yet to be explored.

Dyeing Temperature

The affinity of the dye for the fibre decreases with the increase in temperature and at the same time the hydrolysis of the dye increases due to increased rate of reaction; thus affecting the colour yield. If the rate of reaction is too low, the desired colour might not be the same everywhere over the surface of the dyed material. Just like pH, the temperature of the bath should also follow a certain profile over a certain period of time. Dye manufacturers usually provide the temperature profile for the application of their respective dyestuff.

Electrolyte Concentration

Conductivity is defined as the measure of the concentration of electrolytes present in the bath. It is affected by the salt and alkali injected into the bath. The higher the electrolyte concentration, the higher is the exhaustion rate. However, if the rate of exhaustion is too fast the dye molecules may not be allowed to diffuse inside the fibre before fixation takes place and this may result in unlevelled dyeing.

1.4 Jet Dyeing Machine

Jet Dyeing Machines were developed in the early 1960's for the processing of both woven and knitted fabrics made especially of polyester. The dyeing of these materials required high temperature and pressure and the jet was very attractive for that purpose. Also the liquor ratios of jet dyeing machines are substantially lower than those machines such as winches that required liquor ratio in excess of 1:30 [21]. In Mauritius, most of the cotton knitted fabrics are currently being dyed using reactive dyes on jet dyeing equipment.

The fabric used in a jet dyeing machine is in the form of a rope and the material is propelled by the action of the dye liquor circulated through the jet. Besides, the fabric transport is aided by a motorised reel or winch. The bath is fed from the lowest part of the apparatus tank to the nozzle by means of an impeller pump. The quantity and pressure of the bath liquor through the jet nozzle is controlled automatically by change of rotor speed of the pump.

Chemicals, dyestuffs and other auxiliaries are prepared and added through the addition tank connected to the main dye vessel. Water supply to the main vessel, liquor circulation, heating and cooling of the liquor are controlled automatically through a programmable controller.

1.5 Fuzzy Control

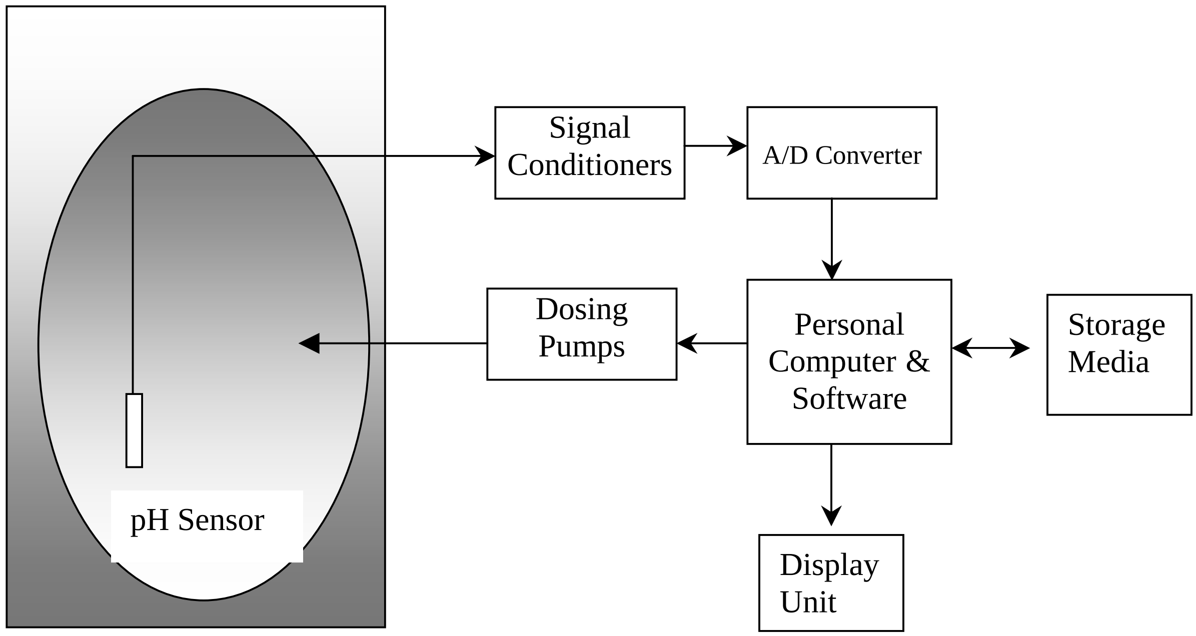
Fuzzy control is a modern control method that uses a control algorithm based upon human control logic. The controller mimics the human decision-making process, whereby an operator takes information, analyses it and makes a decision and applies his decision for controlling the process. The control system uses fuzzy rules and reasoning without the need of complex mathematical modelling to track down and correct the actual values to the set values of a particular process parameter, in this case pH.

Some advantages of using a fuzzy controller in this research work are that it is:

1. Particularly suitable to be used to control not linear processes such as dyeing.
2. Well suited when there is no mathematical process model available. This is currently the case.
3. Easily modified for improving the system performance by changing the user-defined rules.

1.6 Aims And Objectives Of The Project

A block diagram of the proposed system is shown in Fig. 1.1



M10 Jet Dyeing Machine

Figure 1.1: Schematic diagram of the dyeing machine with monitoring system

AIMS

- To develop a fuzzy logic controller to control the dyebath pH of the dyeing of cotton with reactive dyes using a laboratory jet dyeing machine.
- To demonstrate that the control system may be successfully applied to different pH dyeing profiles.
- To study the effect of applying different pH dyeing profiles on the final colour yield of the fabric.

OBJECTIVES

1. Determination of the effect of dyeing conditions on dyebath pH.
2. Selection of appropriate pH sensors, accessory equipment and dosing pumps for the automated system.
3. Design and construction of a driver circuit which would actuate the dosing pumps
4. Development of a software that would allow the input of different pH profiles and acquire data.
5. Development of a suitable algorithm for a fuzzy controller to allow control of dyebath pH during dyeing with different pH profiles.
6. Development of a computer software for (i) implementing the fuzzy controller (ii) communicating with the human operator for specifying process parameters and (ii) for controlling the dyebath pH according to the set profiles.
7. Testing and fine-tuning of the controller system.
8. Measurement of the dyed fabric to determine the colour yield of the fabric

CHAPTER 2

HARDWARE DESIGN

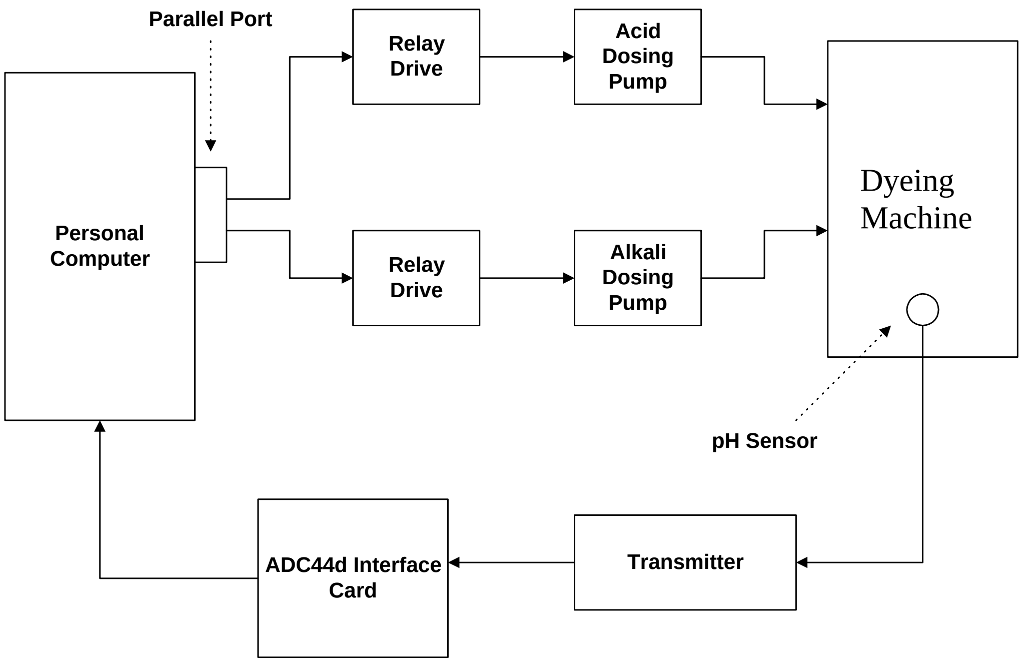


Figure 2.1 Block Diagram of System Hardware

Figure 2.1 shows a block diagram of system hardware. The three main components of the system are the M10 jet dyeing machine with the appropriate sensors, a personal computer with the developed software and the pumps. The jet dyeing machine allows the dyeing process to be carried out and provides input to the monitoring system, the personal computer is used to monitor and control the pH of the dyebath, and the pumps permit the necessary corrective action to be taken.

2.1 The Jet Dyeing Machine

The Roaches M10 jet dyeing machine is specifically designed for use in laboratories. It is ideal for research and development of fabrics, dyes and chemicals. This machine (Fig. 2.2) has been constructed from A1S1 316 (V4A) high quality stainless steel and clad in an insulated cabinet. It occupies 1.5m^2 and dyes between 2 to 20 metres of fabric in the rope form depending on the weight of the fabric. The volume of the liquor varies between 18 (min) and 80 litres (max) and all parts in direct contact with the process liquor are manufactured in grade 316 stainless steel.

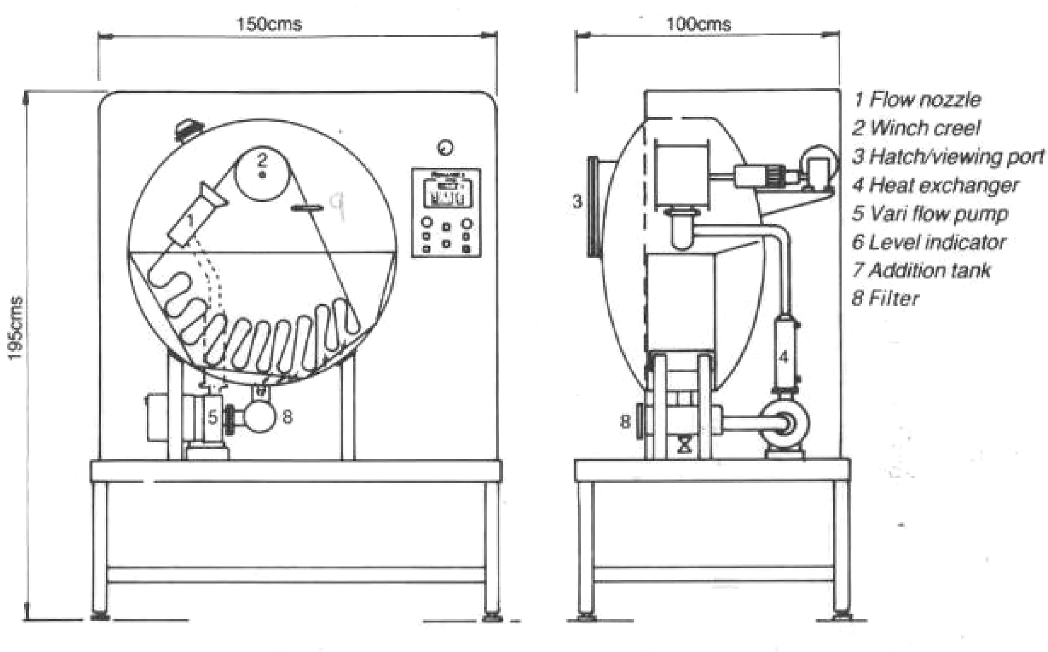


Figure 2.2: Front and Side Schematic Views of the M10 Jet Dyeing Machine.

The continuous fabric rope is transported by the liquor that flows through the jet nozzle (1) under the action of the vari-flow pump, over the winch creel (2), through the fabric guide hoop and to the bottom of the kier. The liquor is drawn from the bottom of the vessel through a filter (8) via the pump unit (5) and through the heat exchanger (4) to the jet nozzle (1). The winch creel speed and pump motor speed are controlled via inverters. The machine includes the user-friendly T.P.C 1000MF programmable microprocessor-based controller. It offers operational control of draining and filling in additions to basic time-dependent temperature control and up to 99 programs of temperature profiles may be stored internally. The controller displays the program step, control status, bath temperature, cycle parameters and error codes indicating fault conditions. The technical specifications of the controller are listed in Table 2.1.

Table 2.1 The T.P.C 1000MF Technical Specifications

Supply Voltage	240V AC, 50 Hz
Input	Temperature Sensor IC
Output	Solid State switching up to 1.0A of heating/cooling.
Operating Ambient Temperature	Max 65˚C
Control Temperature Range	0-145˚C
Control Thermostat Time Range	10 sec, 9 h 50 min
Control Rate	0-16˚C depending on the dyeing machine.
Dimensions	Panel space require 225x 135 (220 depth)
Options	Drain, Fill (hot or cold), Display in ˚C or ˚F
Motor Control	(4-20mA) with forward & reverse functions.

2.2 The pH Sensor

The requirements of the pH sensor were based on the recommendations of the M10 dyeing machine suppliers. The sensor should be able to withstand severe dyeing conditions for exhaust reactive dyeing of cotton with maximum operating temperature of 80^{o}C. It is based on the electrode method and pH electrodes form part of a closed electrical circuit as shown in Figure 2.3.

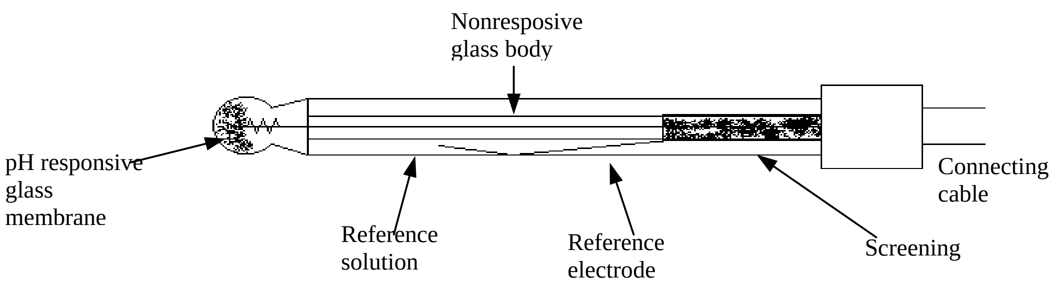


Figure 2.3: pH Probe Assembly

The pH sensor used during this project consisted of a pH/ redox electrode of length 120mm, the probfit CPA 440 assembly to hold the electrode, a pH/redox-measuring instrument and a measuring cable. It was a CPS11 pH sensor from Endress+Hauser, which measures pH values from 0 to 14, at a maximum temperature of 130^{o}C and maximum pressure of 6 Bars [22]. Further details regarding the sensor can be found in Appendix.

The pH measuring system was calibrated by using buffer solution of pH 4 and pH 7. Electrodes need frequent cleaning and calibration since soiling may impair the function of the electrode to such extent that it ceases to work entirely. For example, coatings on the pH sensitive glass membrane may cause poor response, low sensitivity / slope and unstable measured values.

Cleaning of the electrodes can be done by using a suitable cleaning solution or a soft brush and then rinsing it with distilled water. The transmitter or signal conditioner for the pH sensor was the Liquisys S CPM223. It was configured to output current signal of 0-20 mA within a range of pH 0-14.

Table 2.2 Specifications of pH Sensor and its Signal Conditioner

pH SENSOR	Manufacturer: **Endress+Hauser**; Model: **CPS11**. Characteristics: 0-14 pH, max temp. : 130˚C, max pressure: 6 Bars.
SIGNAL CONDITIONER	Manufacturer: **Endress+Hauser**; Model: **Liquisys S CPM223**. Characteristics: Signal Output: 0/4-20mA; Resolution: pH 0.01@ 25˚C; Deviation: max 0.5% of measured range.

These pH electrodes are constructed from a special glass that senses the hydrogen ion concentration. This glass is typically composed of alkali metal ions that undergo an ion exchange reaction with the hydrogen ions present in the solution whose pH is being determined. This gives rise to a potential difference. This potential difference is compared with a reference voltage by the measuring instrument before calculating the pH of the solution.

2.2.1 Placement of the pH Sensor onto the Dyeing Machine

The pH sensor was placed at a suitable location onto the machine so that it is always into contact with the circulating liquor but without obstructing its flow. A hole was therefore drilled at the base of the kier to fit the sensor at the required angle and the fitting was done so that it could be removed for calibration.

2.3 Signal Conditioner/ Transmitter (CPM 223)

The CPM transmitter outputs 0-20mA or 4-20mA signals while the ADC card accepts 0-10V signals. Therefore, to convert the current signal to a voltage signal, a 500Ω resistor is connected in series with the transmitter output. This is because the maximum current and maximum voltage are respectively, 20mA and 10V. Using V=IR, we have R=10/20,000=500Ω [22]. For convenience, the transmitter is configured to output 0-20mA such that 0mA is equivalent to 0V.

Also the signal output by the pH sensor is a very small voltage. It has to be conditioned in order to be of use in the following stage of the system. First, the small voltage is amplified and processed so that the output voltage is proportional to the pH. This is accomplished by a CPM 223 transmitter from Endress+Hauser, details of which can be found in Appendix. Finally, the output of the transmitter is converted to a digital signal which can be fed to the control program. The conversion is made by using the available analog-to-digital converter on the ADC-44d interface card

2.4 ADC44d Interface Card with an A/D Converter

The interface card is responsible for converting the analog voltage to digital words. It is a PC compatible card with 16 single-ended or 8 differential analog input signals.

The card configuration is as follows:

1. Base address 200_{hex}
2. Inputs set to unipolar (0 to +10V)
3. Gain x1
4. Single 16 channel inputs (only 1 channel will be used)
5. I/O mode
6. Manual channel select
7. I/O start convert begins each conversion

Configurations 1 and 2 are achieved by modifying jumper blocks on the card (JP4 and JP2, respectively). The pH sensor is connected to pin 3 of the card.

The card resolution is 2.4mV (range divided by $2^{\text{number of bits}}$) and that of the pH sensor, is ±1%. Therefore, the level of resolution is more than adequate for the present application [22].

2.5 The Personal Computer

The personal computer used for this project, as shown in Fig. 2.4, was equipped with a 75 MHz microprocessor, 64Mb RAM and a hard disk with a capacity of 4Gb. Its operating system is Windows 98 and Turbo C software has been installed for the purpose of the project. The analogue to digital card was placed in its ISA slot in order to perform A/D conversions of the signal coming from the pH sensor. The parallel port of the computer has been used to send signals out for the actuation of the dosing pumps.

2.5.1 The Parallel Port

The parallel/printer port consists of three ports addresses, namely: the data, status and the control port. For the project only the data port found at address 0x0278 was of interest. The address was obtained by checking the system properties in the device manager of the computer. The parallel port was used to switch ON or OFF the pumps by writing the appropriate word at the data address of the parallel port. The word consisted of 0's; representing 0V for the OFF signal, and 1's representing 5V for the ON signal. These voltage values were obtained by actually measuring the amplitude of the signals, using a voltmeter, at the parallel port of the computer.

Of the eight pins available for data output, the first two pins, namely pins 2 and 3 were used for actuating purposes. Pins 24 and 25 were used as ground. Table 2.3 shows the word assignment for the pins used.

Table 2.3: Word Assignment for the Parallel Port Pins

PINS	PUMP	WORD	STATUS OF PUMP
2	Alkali	0000 0001	ON
2	Alkali	0000 0000	OFF
3	Acid	0000 0010	ON
3	Acid	0000 0000	OFF

Because the printer port at the back of the computer is a female connector, a *DB-25 Male Connector* was fixed to it to allow the transmission of signals to the drivers of the actuating system.

2.6 Fuzzy Controller

A fuzzy logic controller was developed based on C programming language. The software is the heart of the controller and allows the following functions:

- It allows the selection of a pH profile from a defined set
- Acquires and records real-time dyebath pH data
- Compares actual pH values with set values
- Generates appropriate signals to actuating devices for corrective actions

2.7 The Actuating Devices

The Relay Driver Circuit

The current sourcing capability of the PC parallel part is too small for switching on the dosing pumps. A relay drive circuit is therefore necessary so that when the output port for a particular dosing pump switches to Logic 1, the relay coil is switched on and the dosing pump is activated. The drive circuit is shown in Figure 2.4

The parallel port cannot source out large currents. To be on the safe side, the maximum allowable sourcing current of the parallel port is taken as 2.5mA [23].
Therefore, $I_{B(max)}$ = 2.5mA.

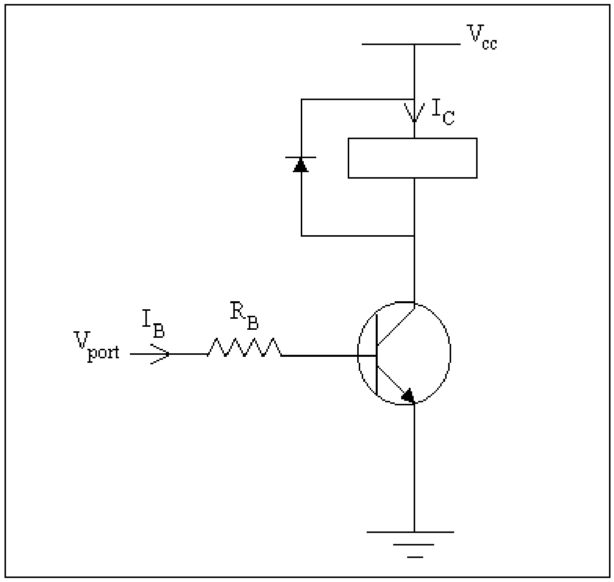


Figure 2.4 Driver Circuit Diagram for Calculation

The transistor acts as a switch that will allow current to flow to the mechanical relay. It is triggered only when it receives 5V signal from the parallel port. A higher voltage, Vcc (12V), develops across the circuit that causes the contact relay, a switch in itself, to engage a higher power signal (240V). The pump is therefore switched ON. The resistor is used to limit the amount of current flowing to the transistor and also prevents the parallel port from overloading.

A diode is placed in parallel to the mechanical relay, an inductive load, to protect the transistor. This is necessary because when the pump is switched OFF, the coil of the relay generates a back emf sufficiently high to damage the transistor. But with a freewheel diode in the circuit, this is avoided.

Calculations For the Driver Circuit

The Resistor, R_B

Given that the parallel port cannot source out large currents, the maximum allowable sourcing current was taken as 2.5mA.

Therefore, $I_{B\ (max)} = 2.5mA$.

Using Fig. 2.5;

$$V_{port} = I_B R_B - V_{BE} \qquad (2.1)$$

$$I_B = \frac{V_{port} - V_{BE}}{R_B}$$

At logic 1, $V_{port} = 5V$

Taking $R_B = 10k\Omega$ and assuming $V_{BE} = 0.7V$

$I_B = (5-0.7)/10x10^3 = 430\mu A < 2.5mA$

A relatively high resistor value was taken in order to have a low current consumption. At the same time, it was ensured that the port would not overload.

The Electromechanical Relay

The power consumption of each dosing pump is 11W, from a 240V rms ac supply. Assuming the pump to operate at unity power factor, its current consumption is given by

$$I = P/V \qquad (2.2)$$

$$= 11/240 = 45.8mA$$

An NT72 (4459) (10A, 240V) electromechanical relay meets these current and voltage requirements. From its datasheet, Current contact rating = 10A > 45.8mA

Voltage contact rating = 240VAC

The Transistor

From the datasheet of the NT72 (4459) relay, its coil ratings are 12V, 0.45W

The coil resistance is measured as R = 320Ω

Now, from the transistor circuit output side, Figure 4.14,

$$V_{CC} = I_C R \tag{2.3}$$

With V_{CC} = 12V, the collector current is calculated as $I_C = V_{CC}/R$ = 37.5mA

The minimum DC current gain of the transistor is therefore,

$$h_{FE} = I_C/I_B = 87 \tag{2.4}$$

A PN2222A transistor satisfies these ratings.

Although the transistor is ON, there is a collector-emitter saturation voltage of about 0.3V. Therefore, it must be ensured that the maximum power rating of the transistor is not exceeded. Otherwise, it would overheat and burnout.

From the datasheet, maximum power rating, P_D = 625mW

From the designed circuit,

$$P_D = V_{CE(sat)} I_C = 0.3 \times 37.5\text{x}10^{-3} = 11.3\text{mW} < 625\text{mW}$$

The Diode

A freewheel diode across the relay coil prevents transient over-voltage spikes due to the energy stored in the coil form damaging the transistor when the latter switches off. The freewheel diode chosen was the IN4001.

An overall circuit diagram with the component values is shown in Figure 2.5

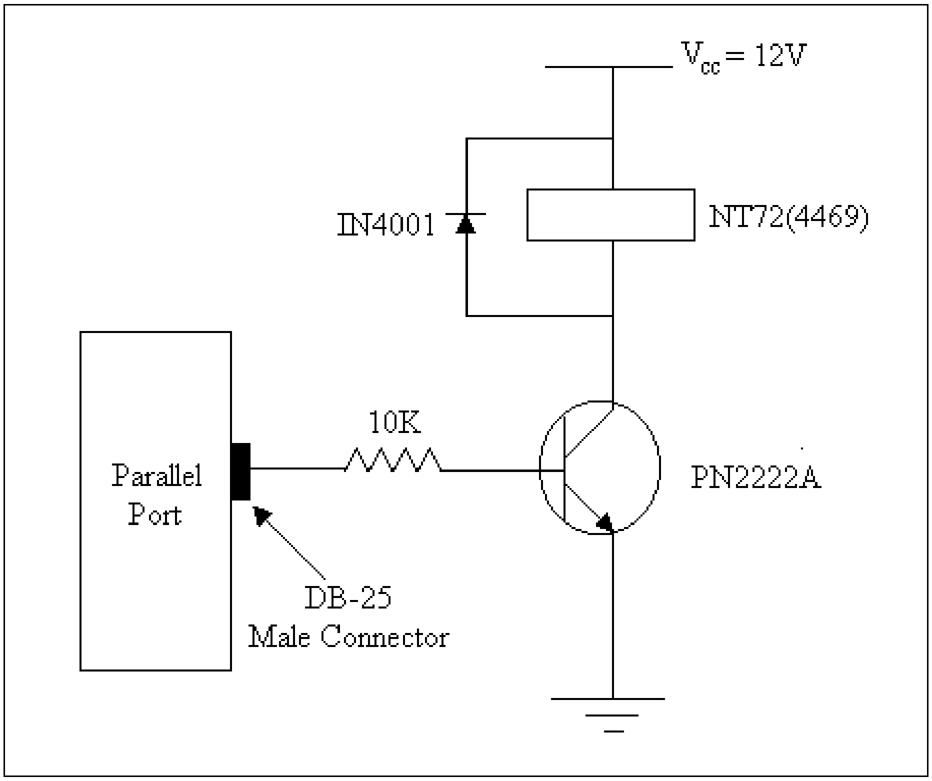


Figure 2.5 Overall Circuit Diagram with Component Values

2.8 Dosing Pumps

Two separate pumps were used to inject the appropriate amount of chemical to the dyeing system in order to maintain the pH at the set values. One pump is used to dose alkali and another for acidic solution. When the actual pH is greater than the set value, acid solution would be injected into the dyebath to bring it back to the set pH. And when the actual pH is lower than the set value one, alkali is pumped into the system.

One of the characteristics of the pumps is that they should be sensitive enough to bring about as small a pH change as possible in regions where the pH changes drastically with chemical addition, whilst at the same time, it should be able to react fairly quickly to large pH changes by dosing enough chemical in that of the graph (Fig. 2.6) where the pH change is less sensitive with dosage volume (the experiment was carried out under the following conditions: temperature of the dyebath: 60^{o}C and liquor ratio: 1:10 with water alone).

It has been also been found that in order to cause any significant pH change to the dyebath liquor, the pumps should be able to deliver at least 0.2-0.3 mL of the concentrated chemicals. It was, therefore, very important to define the specifications of the pumps and these are listed in Table 2.4 for a particular set of concentration of the chemicals and the liquor ratio of the dyeing process used.

Table 2.4 Pumps Specifications

Power supply:	230V ± 10% (50Hz)
Pump capacity:	1.1 l/hr
Max. pressure:	16 BAR
mL/stroke:	0.1
Resistant to NaOH (38° Bé) (Pump for Alkali)	
Resistant to 100% Formic Acid (Pump for Acid)	
Suction delivery line:	DN4 IN
Hose pipe size:	DN8 OUT

The pumps make 180 strokes per minute at 100% capacity. This means that they make 3 strokes every seconds. Hence, in 1 second they deliver 0.3mL, which is the desired flow rate. Note that the pumps have to be calibrated during implementation.

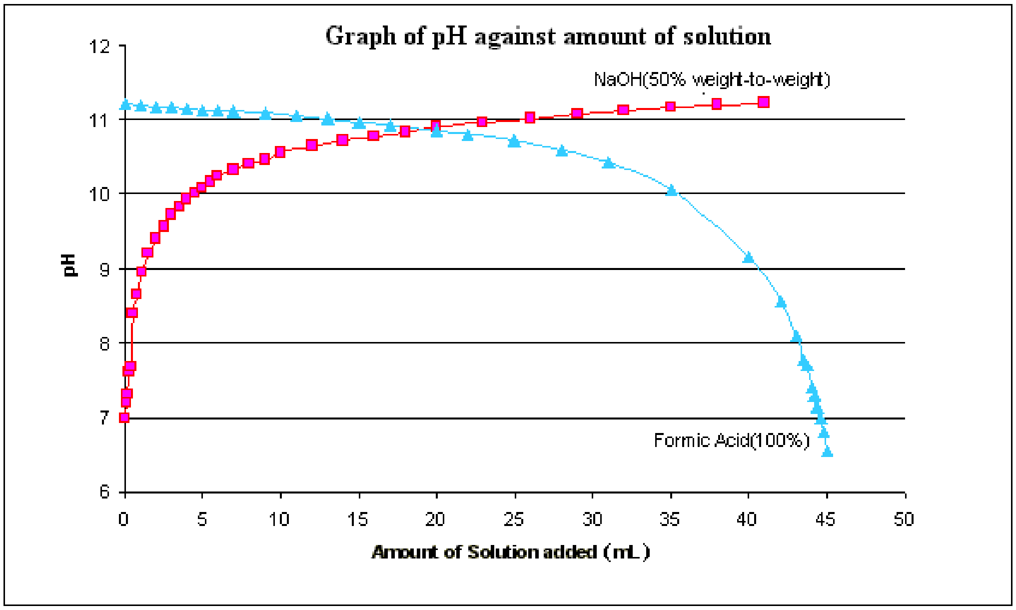


Figure 2.6 Variation of pH with Concentrated Acid/Alkali

It was noted that small amounts of alkali at the start caused large change in pH. As pH increases, large amounts of alkali were needed. The acid behaved logically the other way round. At the start, large amounts of acid were required to make significant pH changes and smaller amount caused large pH change as pH decreased. Also, it was observed that it takes approximately 10 seconds for the bath to stabilize completely.

2.8.1 Dosing Of Chemicals

The chemicals were dosed into the machine at the addition tank of the M10 dyeing machine (Fig. 2.7). The outflow chemical supply tubes of the pumps (acid and alkali) are fixed to the addition tank with its manually actuated 'fill-in' and 'addition' valves fully opened.

Figure 2.7 Addition Tank of Jet Machine

CHAPTER 3

FUZZY CONTROL OF DYEBATH pH

3.1 Introduction

In a typical batch dyeing process of reactive dyes onto cotton, the pH of the dye bath is normally set at an initial value of 7 or slightly less and finishes at a higher pH value of around 11.0   The pH profile from the starting to the end point can take different shapes. One of the objectives of this research work is to develop a control system that would control the dyebath pH during dyeing according to set non-linear pH profiles and to determine the effect of different pH profiles on dyeing quality.

A block diagram of the control system is shown in Figure 3.1, where a closed loop feedback system is used to control the pH. pH control processes are highly non-linear and are characterized by significant transport delays. Therefore any attempt to use conventional Proportional-Integral-Derivative (PID) controllers would cause the actual pH to track the reference profile at certain operating points only, and leaving a large tracking error at other operating points. Moreover with these controllers, the system can also become unstable under certain operating conditions.

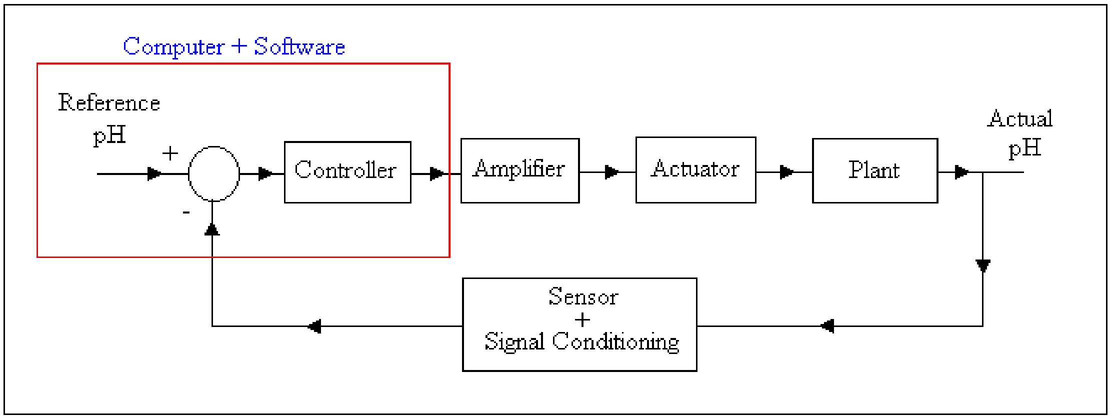


Figure 3.1 Block diagram of pH controlled system

Fuzzy logic has been experiencing growing interest in many industrial applications due to its non-linear features and independence from an accurate system model. The fuzzy controller aims at emulating a human operator by using expert knowledge based on linguistic If-Then rules [24]. The intrinsic non-linear characteristics of the fuzzy controller are used to produce control signals for dosing the right amount of acid or alkali into the dyebath, with the aim of minimising the tracking error between the set pH and the actual pH. This chapter describes the main components of the implemented pH control system and presents the design of a fuzzy controller for implementing the pH tracking system.

3.2 Components of the Proposed System

The proposed system for controlling the pH of the dyeing plant is shown in Figure 3.2. The fuzzy control program is implemented on the Personal Computer (PC). The operator is prompted to choose and define, in a user-friendly environment, the pH profile he wishes to use. Once he starts the operation, the actual pH of the dyeing plant is continuously measured by a pH sensor and sent to the PC. The written program then controls the pH of the dyeing plant by sending appropriate signals to the alkali and acid pumps.

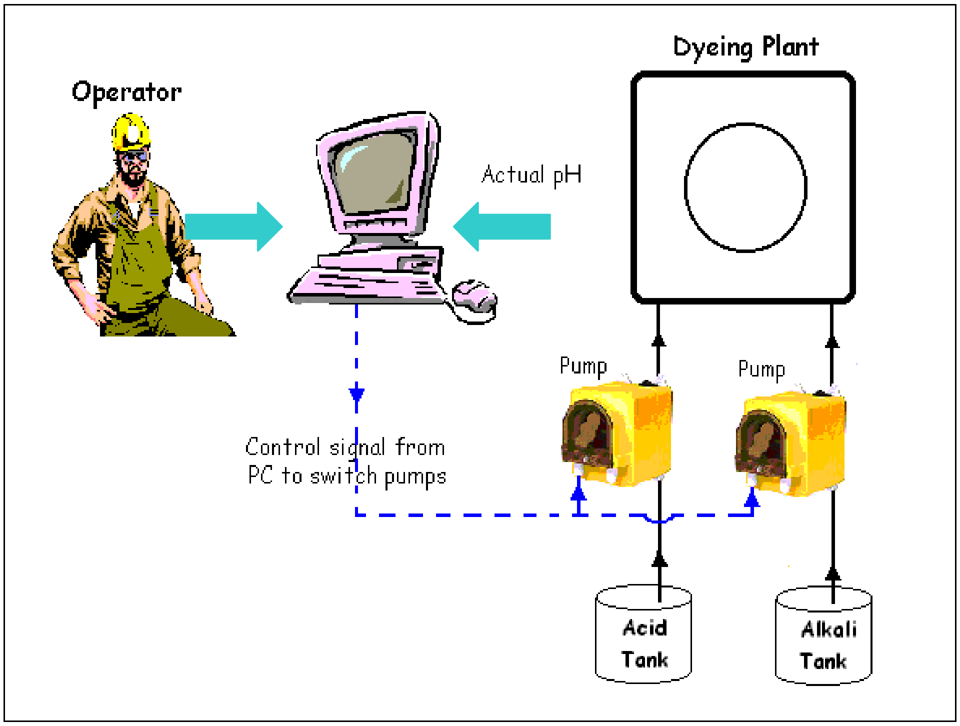


Figure 3.2 Schematic Diagram of Proposed System

The main components forming the system are shown in the block diagram of Figure 3.3.

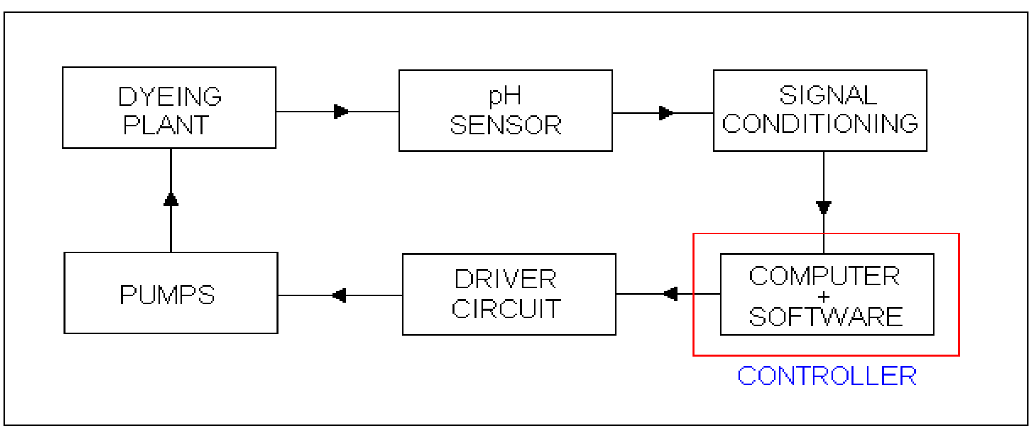


Figure 3.3 System Main Components

3.2.1 Fuzzy Controller

The fuzzy controller is implemented as part of the system software which also performs the following functions:

1. Allows the user to choose and to easily define a desired pH profile from an available list.
2. Acquires the actual pH of the dyebath.
3. Compares the actual pH value with the appropriate reference pH and subsequently processes these information to switch ON and OFF the appropriate pump if need be.
4. Records the actual and its corresponding set pH value at regular time intervals for later assessing the controller response.

3.2.2 Fuzzy Controller Design

Fuzzy control is a modern control method that uses a control algorithm based upon human control logic. The controller mimics the human decision-making process, whereby an operator takes information, analyses it and makes a decision and applies his decision for controlling the process.

Some advantages of using a fuzzy controller in this research work are that it is:

1. Particularly suitable to be used to control not linear processes such as dyeing.
2. Well suited when there is no mathematical process model available. This is currently the case.
3. Easily modified for improving the system performance by changing the user-defined rules.

The structure of the proposed fuzzy controller for the dyeing plant is shown Figure 3.4. The fuzzy system consists of three main stages: fuzzification, fuzzy inference and defuzzification.

The inputs of the controller are the linguistic variables, *pH error* (difference between the desired pH and the actual pH at a given time) and, *pH change in error*. The output is the linguistic variable, *time*, reprensenting the incremental interval during which the appropriate pump should remain ON.

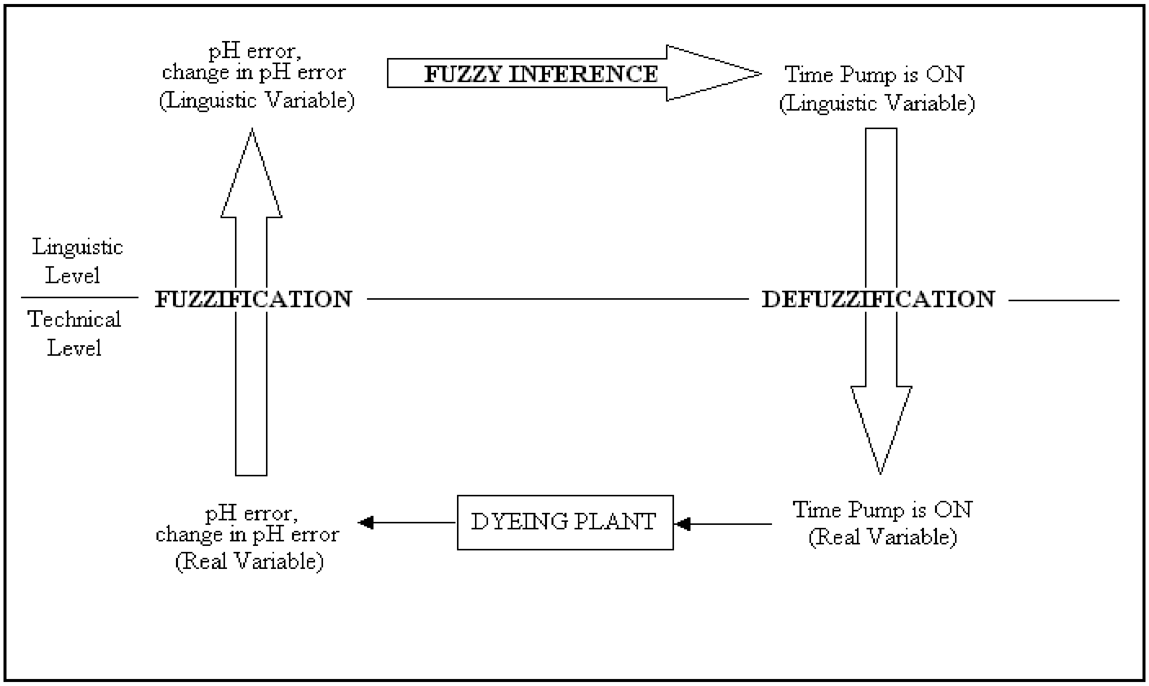


Figure 3.4 Structure of the Proposed Fuzzy Controller

3.2.3 Fuzzification

Fuzzification is the process whereby the real values of input variables are converted into degrees of membership to linguistic values, using membership functions (MBFs). MBFs are mathematical functions that map each value of a given real-life parameter to the membership degree in the linguistic values [24]. A membership degree of 1 means complete membership and 0 means no membership, while any membership degree between 0 and 1 indicates partial membership to the given linguistic variable.

In this project, the real values of the input signals *pH error* and the *change in pH error* are obtained from the process are mapped onto the respective membership functions so as to determine their degrees of membership over the corresponding linguistic values. The chosen linguistic values for the two inputs are: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (PM) and

Positive Big (PB). The MBFs for *pH error* and *change in error* are shown in Figures 3.5(a) and 3.5(b), respectively. The *error* and *change in error* are respectively defined as:

$$e(k) = pH_{ref}(k) - pH(k) \quad \textbf{(3.1)}$$

and

$$\Delta e(k) = e(k) - e(k-1) \quad \textbf{(3.2)}$$

where $pH_{ref}(k)$ and $pH(k)$ refer to the k^{th} time instant of the reference pH and the actual pH, and $e(k-1)$ is the error value of the previous sample.

For a given set of input error and change in error, one or more linguistic variable can assume a non-zero membership value.

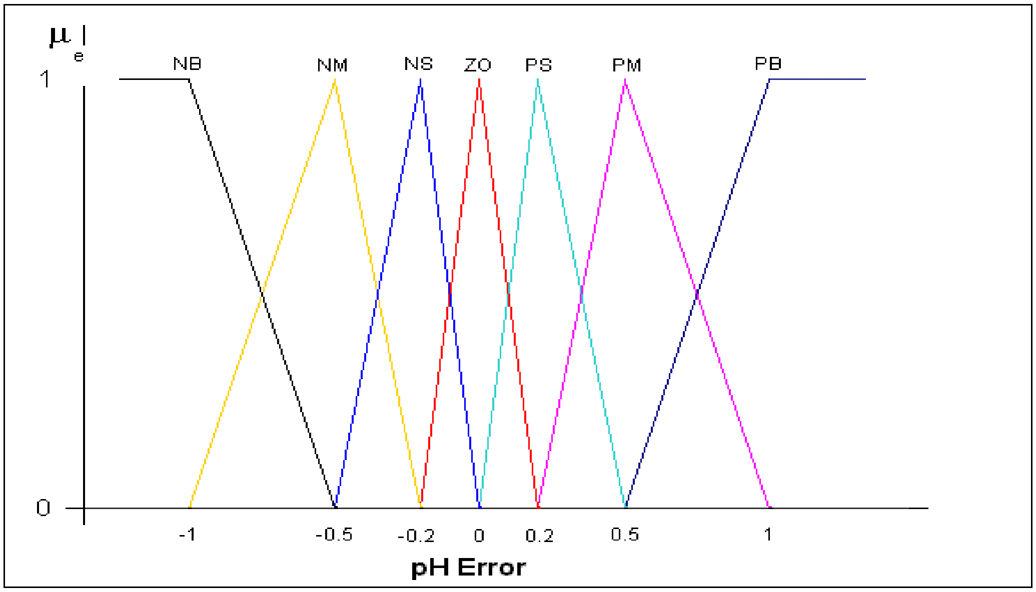


Figure 3.5(a) Membership Functions for pH Error (μ_e: Degree of Membership)

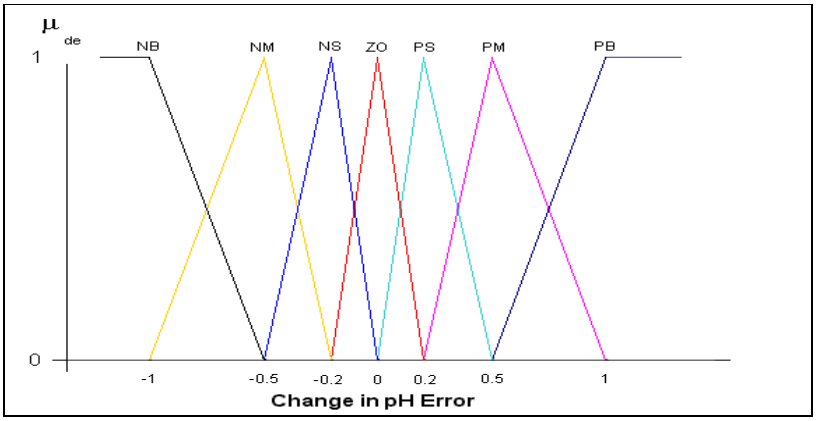


Figure 3.5(b)MBFs for Change in pH Error(μ_{de}: Degree of Membership)

The MBFs were obtained after doing several experiments to better understand the process. Firstly, it was concluded that an error of 1 pH value should be considered as big. So above ±1, the error was made to saturate. Between the two extremes, Zero and Big, a middle term referred as Medium error was obtained and it represented ±0.5 pH errors. Secondly, a last term was included between Zero and Medium, referred to as Small. No more than seven terms were used because the short-term human memory can compute only up to seven symbols at a time [24].

Triangular MBFs were used because: -

1. They are simple and sufficient to design the fuzzy pH control system.
2. They are easy to interpret.
3. They can be easily and efficiently used to compute the degree of membership.

To compute the degree of membership, the error is substituted in the appropriate linear equations. The following linear equations were developed for the membership functions relating to the error, *e(k):*

Range $e(k) \geq 1$

PB: $\mu_e = 2\, e(k) - 1$ **(3.3)**

Range $0.5 \leq e(k) < 1$

PB: $\mu_e = 2\, e(k) - 1$ **(3.4)**

PM: $\mu_e = -2\ e(k) + 2$ **(3.5)**

Range $0.2 \leq e(k) < 0.5$

PM: $\mu_e = 3.33\ e(k) - 0.667$ **(3.6)**

PS: $\mu_e = -3.33\ e(k) + 1.667$ **(3.7)**

Range $0 \leq e(k) < 0.2$

PS: $\mu_e = 5\ e(k)$ **(3.8)**

ZO: $\mu_e = -5\ e(k) + 1$ **(3.9)**

Range $-0.2 \leq e(k) < 0$

ZO: $\mu_e = 5\ e(k) + 1$ **(3.10)**

NS: $\mu_e = -5\ e(k)$ **(3.11)**

Range -0.5 ≤ ‘e’ < -0.2

NS: $\mu_e = 3.33\ e(k) + 1.667$ **(3.12)**

NM: $\mu_e = -3.33\ e(k) – 0.667$ **(3.13)**

Range –0.5 ≤ ‘e’ < 1

NS: $\mu_e = 2\ e(k) + 2$ **(3.14)**

NM: $\mu_e = -2\ e(k) – 1$ **(3.15)**

Range $e(k) \leq -1$

NB: $\mu_e = -2\ e(k) – 1$ **(3.16)**

For example, error = 0.6. It implies that the error is positive medium and positive big Substituting 0.6 in the appropriate equations:

PM: $\mu = -2(0.6) + 2 = 0.8$

PB: $\mu = 2(0.6) – 1 = 0.2$

Therefore an error of 0.6 after fuzzification is interpreted as positive medium to a degree of 0.8 and positive big to a degree of 0.2.

The same procedures are adopted to develop the MBFs for the change in pH error, $\Delta e(k)$. The Zero, Small, Medium and Big change in pH error are quantified. Since the respective MBFs shown in Figure 3.5(b) are identical in shape to those in Figure 3.5(a), Equations(3.3) to (3.16) apply in the computation of the degree of membership, by replacing μ_e by μ'_e.

3.2.4 Fuzzy Inference

In the Fuzzy Inference stage, the controller uses the input membership degrees for a given input combination and consults a rule base so as to determine the control decision to be taken. In the present work, this control decision represents the time during which a dosing pump should remain ON. The rule base contains the possible input-output combinations in terms of linguistic rules. The complete rule base for the designed fuzzy controller is given in Table 3.1. An example of a linguistic rule can be:

IF *e(k)* is PM **AND** *Δe(k)* is PS **THEN** *Δt* is NS

where *Δt* is the incremental time during which the pump should remain ON to bring the actual pH to the set pH.

The *IF* part of the rule is called the *Premise* while the *THEN* part is the *Consequent*. One or more rules can fire for a given value of *e(k)* and *Δe(k)*. Since linguistic values are not precise representations of the quantities that they describe, linguistic rules are not precise either [24]. The result of the Fuzzy Inference process is a combination between the results of the rules that fire.

Table 3.1 Rule Base of Proposed Fuzzy Controller

Change in Error (*Δe(k)*)

Error (*e(k)*)	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	*NB*	*NB*	*NB*	*NB*	*NM*	*NS*	*ZO*
NM	***NB***	*NB*	*NM*	*NM*	*NS*	*ZO*	*PS*
NS	*NB*	*MN*	*NS*	*NS*	*ZO*	*PS*	*PM*
ZO	*NM*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PM*
PS	*NM*	*NS*	*ZO*	*PS*	*PS*	*PM*	*PB*
PM	*NS*	*ZO*	*PS*	*PM*	*PM*	*PB*	*PB*
PB	*ZO*	*PS*	*PM*	*PB*	*PB*	*PB*	*PB*

The incremental time, *Δt*, is also described in terms of linguistic values, which are characterized by output membership functions, as shown in Figure 3.6. The chosen linguistic values for *Δt* are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (PM) and Positive Big (PB). There are 7 linguistic terms that describe both inputs. So the total number of rules is 49 (7^2).

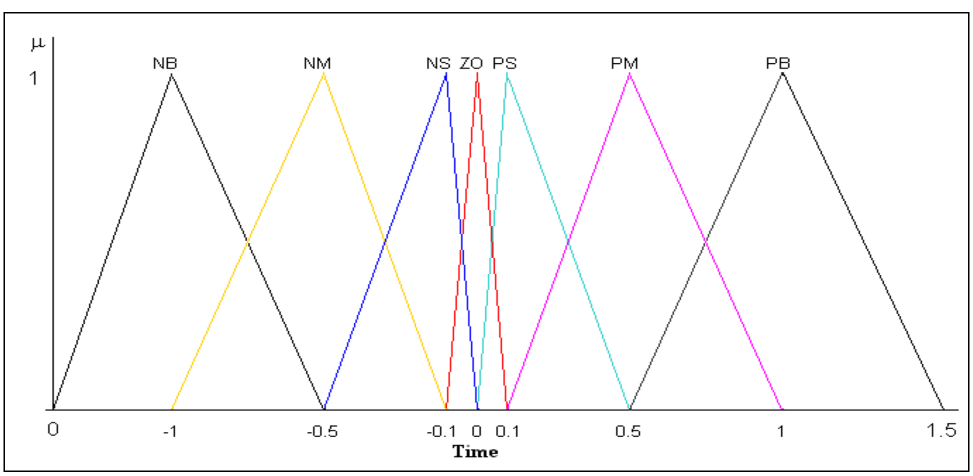


Figure 3.6 Membership Functions of Incremental Time, Δt

These fuzzy control rules have been developed based on two criteria:

1. Bring the deviation to the desired response rapidly.
2. Reduce the rise time.

Computation of the fuzzy inference result for this research work employs the MAX/MIN method and it consists of two parts known as: -

1. Aggregation
2. Composition

Each time the fuzzy controller is called, the fuzzy inference is computed for the 49 rules.

3.2.5 Aggregation

Aggregation is the process of obtaining a result from the *IF* part, consists of two components: the pH error, $e(k)$ and the change in pH error, $\Delta e(k)$. To obtain a result from these components, the fuzzy AND operator is employed. This operator takes the minimum from the error and the change in error. Table 3.2 shows the results of the fuzzy AND operator.

Table 3.2 Results of Fuzzy AND Operator

A	B	Min (A,B)
0	0	0
0	1	0
1	0	0
1	1	1

3.2.6 Composition

Composition is the process of obtaining a result for the *THEN* part of the rule. The latter part defines the action to be taken and its degree of validity is given by the result of the aggregation. It may happen that the same action is to be taken but with different degree of membership. In these situations, the results have to be combined. This is done by using the fuzzy OR operator which takes the maximum of these results. Table 3.3 shows the results of the fuzzy OR operator.

Table 3.3 Results of Fuzzy OR Operator

A	B	Max (A,B)
0	0	0
0	1	1
1	0	1
1	1	1

3.2.7 Defuzzification

The result of the Inference stage is a combination of the individual Consequent parts of the firing rules. Deffuzification converts this combination of Consequents into a single real or crisp output, which represents a best compromise among the Consequents. For the pH control process, this single output represents the incremental time delay, in seconds, during which the appropriate pump is activated.

The Center-of-Maximum (CoM) method [24] is used for the proposed fuzzy controller since it delivers the best compromise time delay. Thus a very small change in any of the inputs cannot produce an abrupt change in the output, hence avoiding the possibilities of instabilities and oscillations in the output response.

The output linguistic values and their corresponding real values are related by MBFs, as shown in Figure 3.6. Negative values of Δt imply that acid should be dosed and positive implies that alkali should be dosed. The universe of discourse on the **time axis** has been normalized in the range [-1.5,1.5]. The values on the vertical axis represent the degree of membership, μ, of the MBFs.

Computing the CoM is a two-step approach: -

1. Compute the typical values of the corresponding terms that have been fired during fuzzy inference. This is achieved by taking the maximum of their MBFs.
2. Find the best compromise crisp value. This is computed by balancing out the fuzzy inference results about that crisp value. It is analogous to calculating the moment of a force about a point. The force is replaced by the degree of membership.

For example, the result of the fuzzy inference is that, Δt should be *PM* to a degree of 0.2 and *PB* to a degree of 0.8, as shown in Figure 3.7.

Let X = defuzzified time delay

Typical time value of PS = 0.5, with degree 0.2

Typical time value of PB = 1.0, with degree 0.8

Therefore, 0.2(X-0.5) = 0.8(1-X)

Hence, X = 0.81 secs

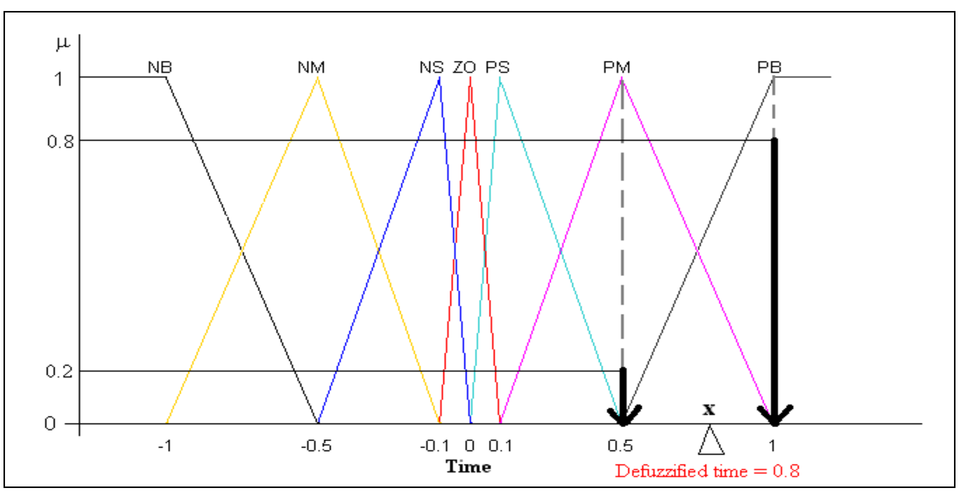


Figure 3.7 Illustration of CoM Defuzzification

3.2.8 Fuzzy Controller Input And Output Gains

A block diagram of the complete fuzzy controller is shown in Figure 3.8. In Figures 3.5 and 3.6, the universes of discourse for the input and output variables of the fuzzy controller have been normalized within typical ranges of [-1, 1] and [-1.5, 1.5], respectively. However, the range of individual MBFs and the universes of discourse largely influence the dynamic response of the pH control system. A convenient method of tuning the controller so as to obtain the desired pH response is to introduce scaling gains at the inputs and the output of the fuzzy controller, so that the MBFs can effectively be expanded or compressed by varying the gains. The effective inputs to the fuzzy controller thus become:

$$e'(k) = k_e[pH_{ref}(k) - pH(k)] \quad \textbf{(3.17)}$$

$$\Delta e'(k) = k_{\delta e}[e(k) - e(k-1)] \quad \textbf{(3.18)}$$

while the output incremental time delay is scaled to

$$\Delta t'(k) = k_u \Delta t \quad \textbf{(3.19)}$$

The scaling gains are tuned through computer simulations and experiments so as to obtain the desired dynamic response.

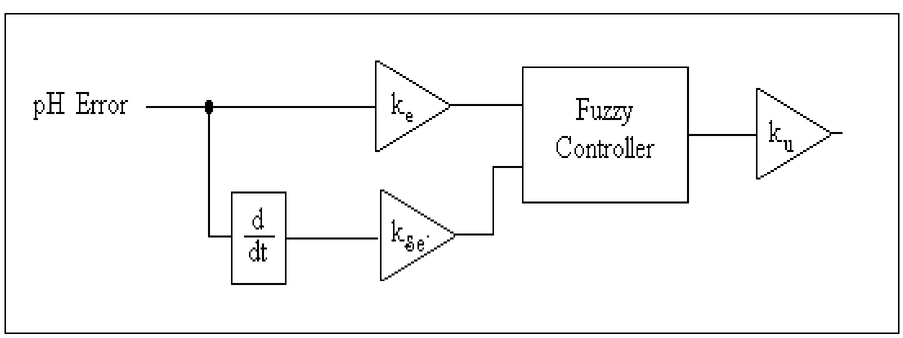


Figure 3.8 Block Diagram Of The Fuzzy Controller With Input/Output Gains

3.3 pH Reference Profiles

Four types of pH profiles namely, Ramp, Quadratic, Exponential and User-Defined, are proposed to the operator. The first three profiles are monotonic functions of time so that their gradients are always positive. Finally the user-defined profile was also included in order to provide maximum flexibility for investigating any other plausible pH profile.

For a given type of profile, the operator is prompted to enter the total alkali dosing time T, pH at the start and at the end of the process, and relevant parameter(s) for varying the curvature of the time varying function, thus providing flexibility in defining a profile. For all the dyeing performed, the pH of the dyebath at the start was 6.78 and the final pH 10.92. Also, the dosing time T and the fixation time (time after which all alkali has been added) were kept constant for the experiments.

3.3.1 Ramp Profile

The simplest of the proposed profiles is a linear one. The general ramp pH profile is defined as

$$pH(t) = m \times t + pH(0) \qquad \textbf{(3.20)}$$

where *m* represents the gradient of the line, and *pH(0)* is the starting value of the pH.

The characteristic is shown in Figure 3.9. The parameters that are entered are: *pH(0*), the final pH value at the end of the process and the total alkali dosing time. With these values, the control program computes the value of *m*.

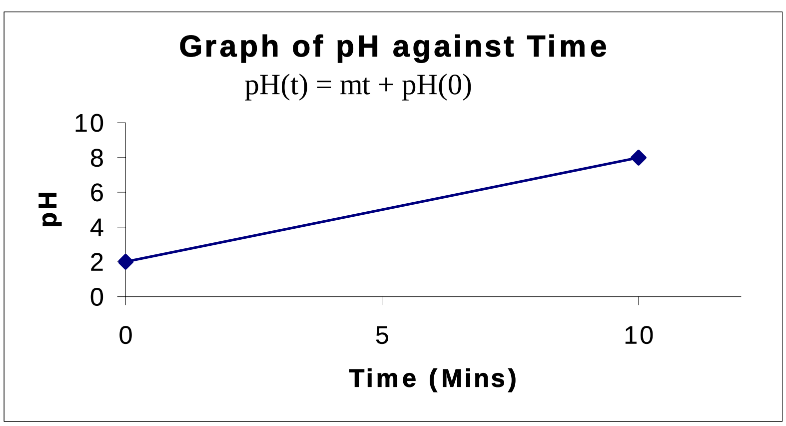


Figure 3.9 Example of a Ramp pH Profile

3.3.2 Quadratic Profile

Profiles under the Quadratic class are shown in Figure 3.10. Their general equation is given by

$$pH(t) = at^2 + bt + pH(0) \qquad \textbf{(3.21)}$$

where *a* and *b* are constants.

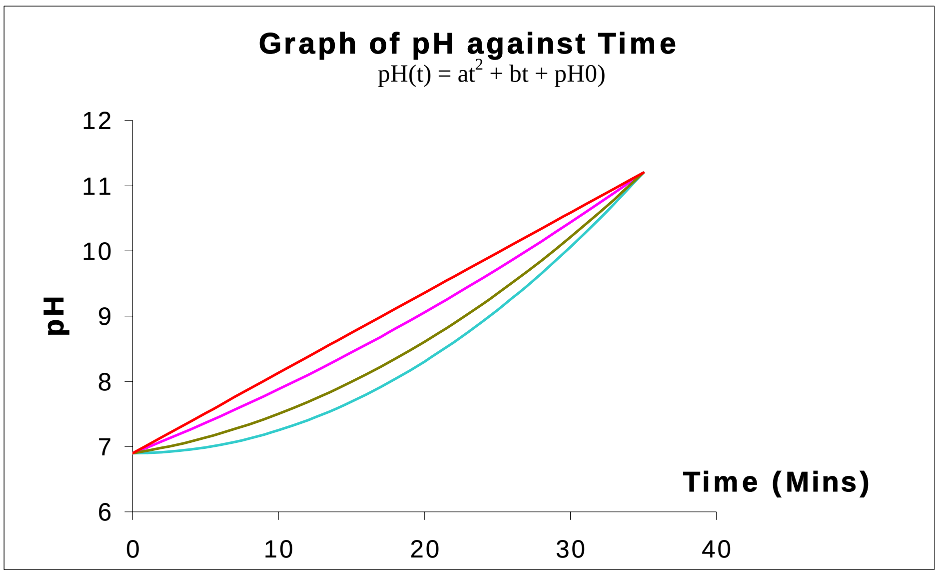


Figure 3.10 Examples of Quadratic pH Profiles

It is desired that the curve has a minimum point. To satisfy such a condition,

$\frac{d^2pH}{dt^2} < 0.$

Therefore, $b > 0$ and $0 < a < [\, pH(t) - pH(0)\,]/t^2$

The parameters to be entered by the operator are: *pH(0)*, the total alkali dosing time, *T*, *pH(T)* and the value of *a*. The latter determines the degree of curvature of the profile. With these values, the control program the value of *b*. To meet the experimental constraints, the following condition has to be satisfied: $0 \leq a \leq [pH(T) - pH(0)]/T^2$.

3.3.3 pH Exponential Profile

Figure 3.11 shows typical profiles under the Exponential class. A general expression describing such a profile is

$$pH(t) = a.exp(t/b) - a + pH(0) \qquad \textbf{(3.22)}$$

where *a* and *b* are constants for a given curve. The experimental constraints are respected if the following condition is satisfied: $a \leq 1$. The parameters to be entered by the operator are: *pH(0)*, the total alkali dosing time, *T*, *pH(T)* and the value of *a*. The latter determines the degree of curvature of the profile. With these values, the control program computes the value of *b*.

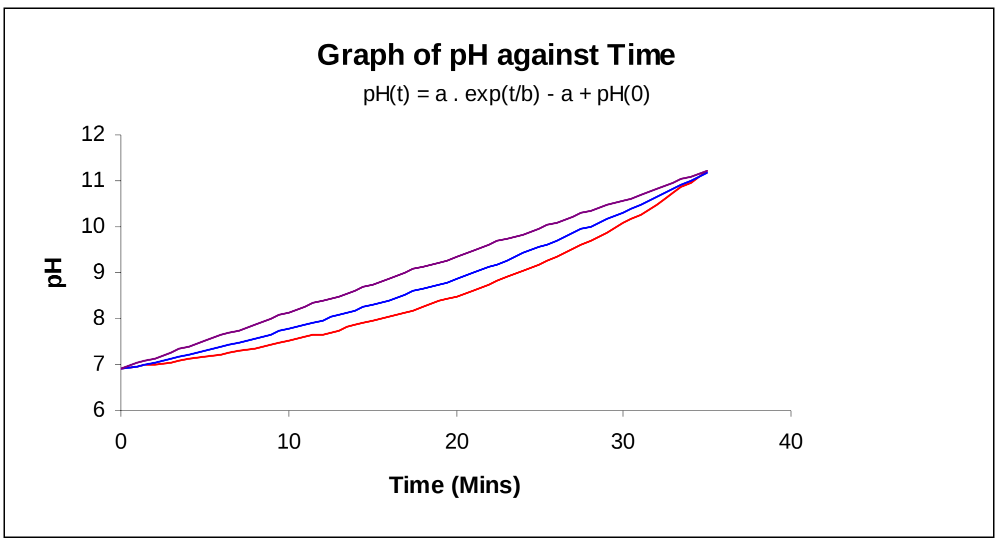


Figure 3.11 Examples of Exponential pH Profiles

3.3.4 pH User-Defined Profile

In this last mode, the pH user-defined profile, the operator is able to program the controller to make the pH vary in any shape, as shown in Figure 3.12. This is achieved by prompting the operator to enter the desired pH values and the times at which those values are reached, as well as the total alkali dosing time (*T*).

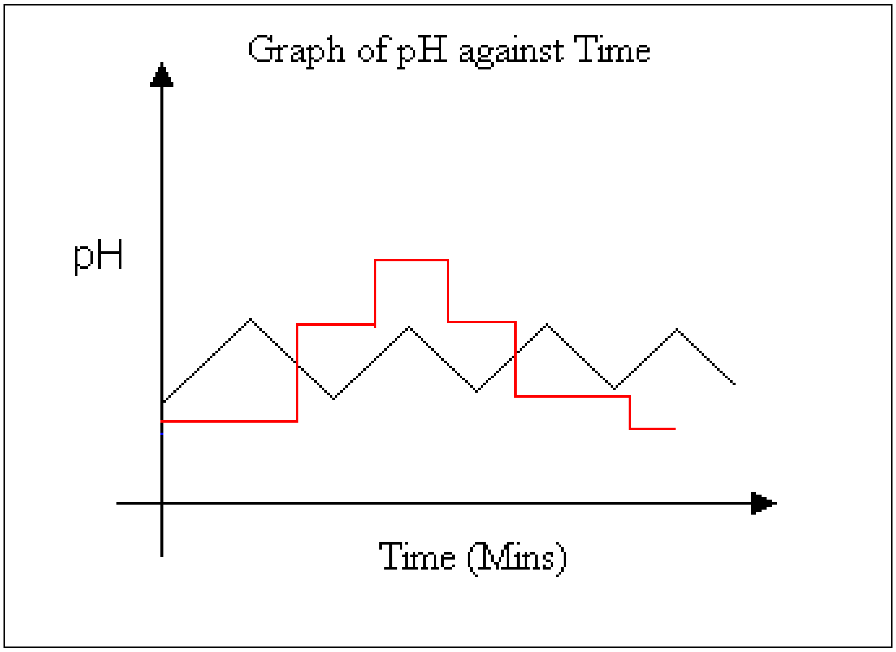


Figure 3.12 Examples of Possible User-defined Profiles

3.4 Control Flowchart

Figure 3.13 shows a general flowchart for controlling the pH of the dye bath. The detailed development of the software is discussed Chapter 4.

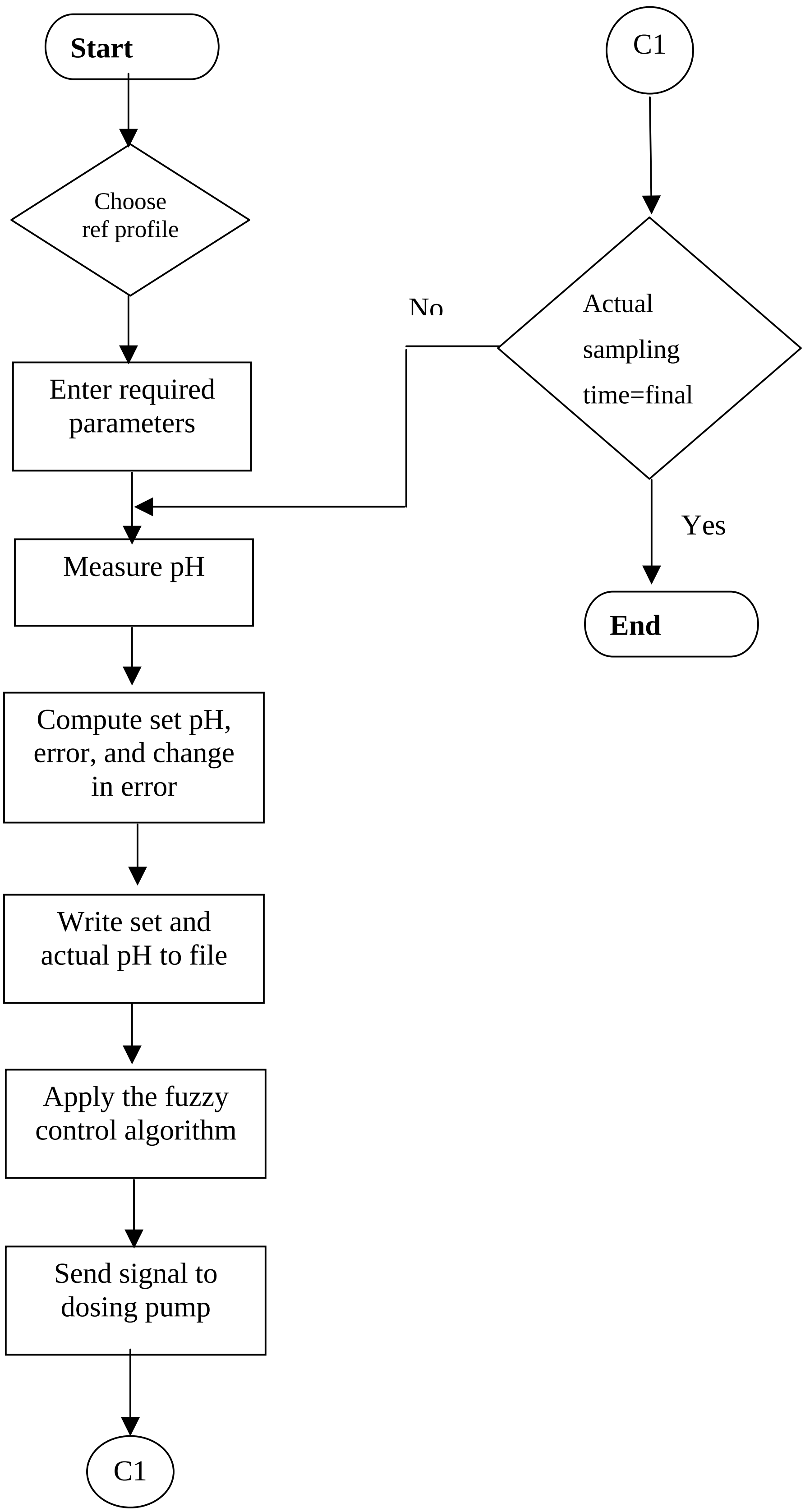


Figure 3.13 General Flowchart for pH control

CHAPTER 4

SOFTWARE DESIGN

4.1 Introduction

The software developed for this research work performs the following main functions:

(i) Communication with the human operator to specify the type of pH profile desired, together with the starting/ finishing pH values, and profile-specific parameters.

(ii) Acquisition of actual pH values from the dye bath in digital form through the ADC44d interface card.

(iii) Implementation of the fuzzy control algorithm described in Chapter 3, with the aim of tracking the desired pH profile with minimum error, by appropriate dosing of chemicals through the actuating pumps.

(iv) Selection of the appropriate dosing pump, depending on whether acid or alkali is to be dosed, and sending appropriate drive signals to the pumps.

The software is coded in modular programming style using C language. The program structure of the software is shown in Figure 4.1. It consists of 16 modules, all compiled to an object file. In this chapter, the algorithms for the various software modules are described.

This chapter also describes the hardware design, which consists of:

(i) Specifying the type of pH transmitter, and the interface card for acquiring data from the dyeing plant.

(ii) Designing relay drive circuitry so as to switch dosing pumps ON and OFF from the interface card.

(iii) Specifying acid and alkali dosing pumps for precise pH adjustment of the dye bath.

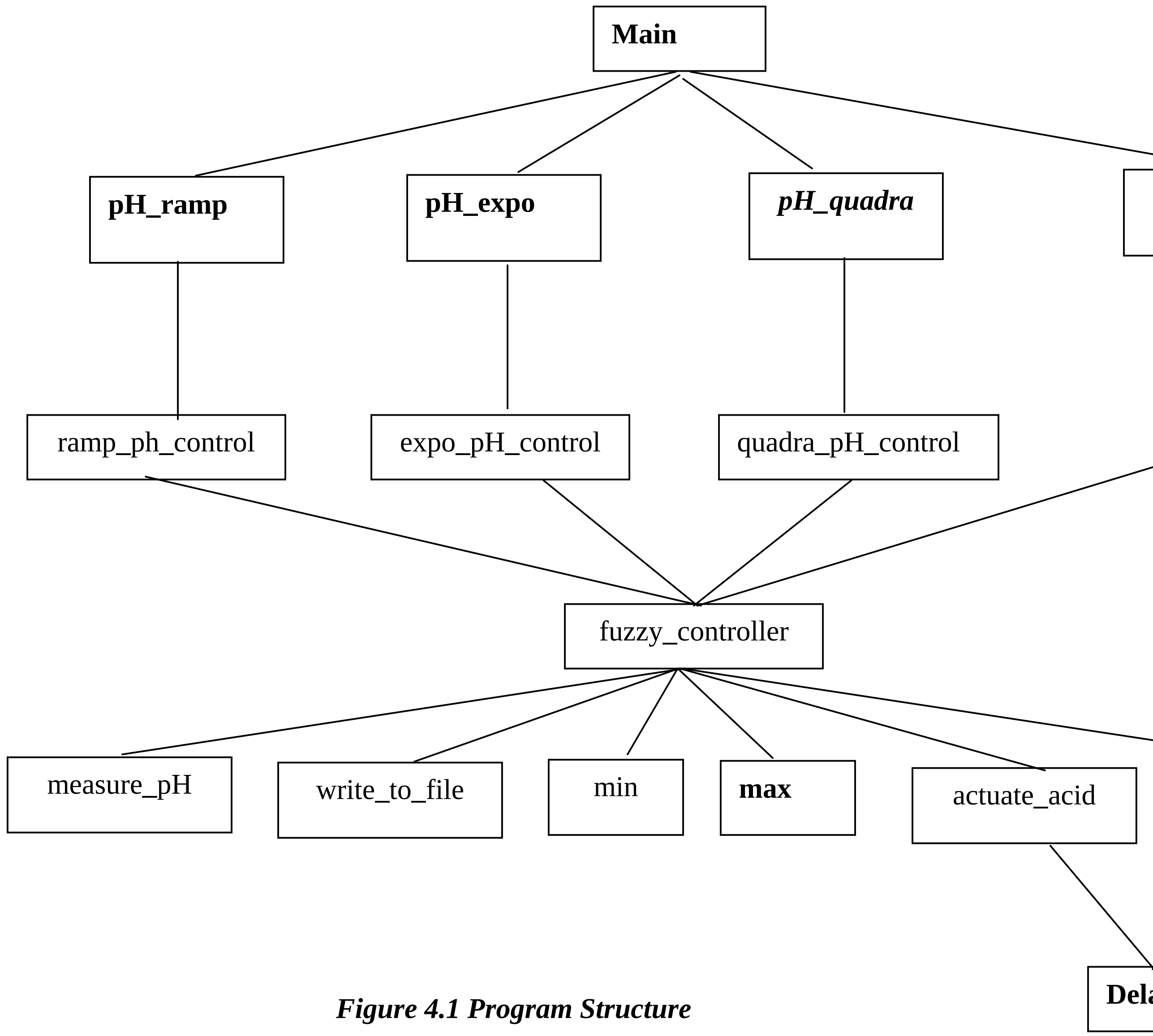


Figure 4.1 Program Structure

4.2 Software Modules

The following sections consist of the development of each of the different modules that make up the software, based on the program structure shown in Figure 4.1.

4.2.1 Main

This is the main module which displays a menu showing the different proposed profiles as well as an 'exit program' choice. The operator is prompted to choose one of the available options. If an incorrect option is selected, an error message appears. It informs the operator that an incorrect choice has been made and to press any key to exit the program.

4.2.2 pH_Ramp

In this module, the operator is shown the equation of the chosen profile and the meaning of the different terms. He is prompted to enter the different required dyeing parameters, that is, the total processing time, initial and final pH. The operator is prompted to confirm the start of the process by pressing any key from the keyboard. The values entered are passed to the next module. The flowchart of the pH_ramp module is given in Figure 4.2.

4.2.3 pH_Expo & pH_Quadra

Like in the previous modules, pH_expo.obj and pH_quadra.obj display the equation of their respective profile and the meaning of the different terms. Again the operator enters the different dyeing parameters. In Chapter 3, it is mentioned that the value *a* has to be within a certain range to meet the experimental constraints. If this is not the case, a message appears on the screen to tell the operator the valid range of a. When the correct value of a has been entered, the operator has to confirm the start of the process by pressing any key. From there, the values entered are passed to their next corresponding module. The flowcharts of these modules are shown in Figure 4.3 and Figure 4.4.

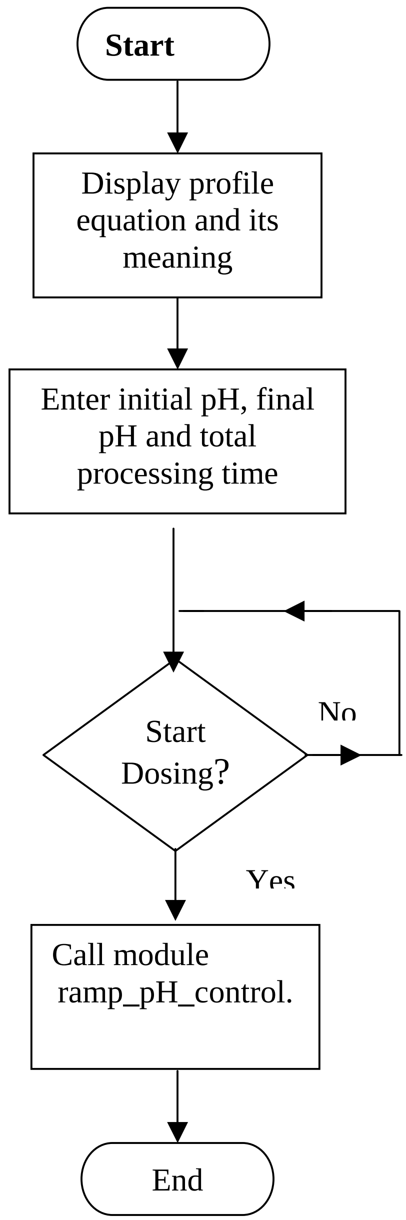


Figure 4.2 Flowchart of the pH_Ramp Module

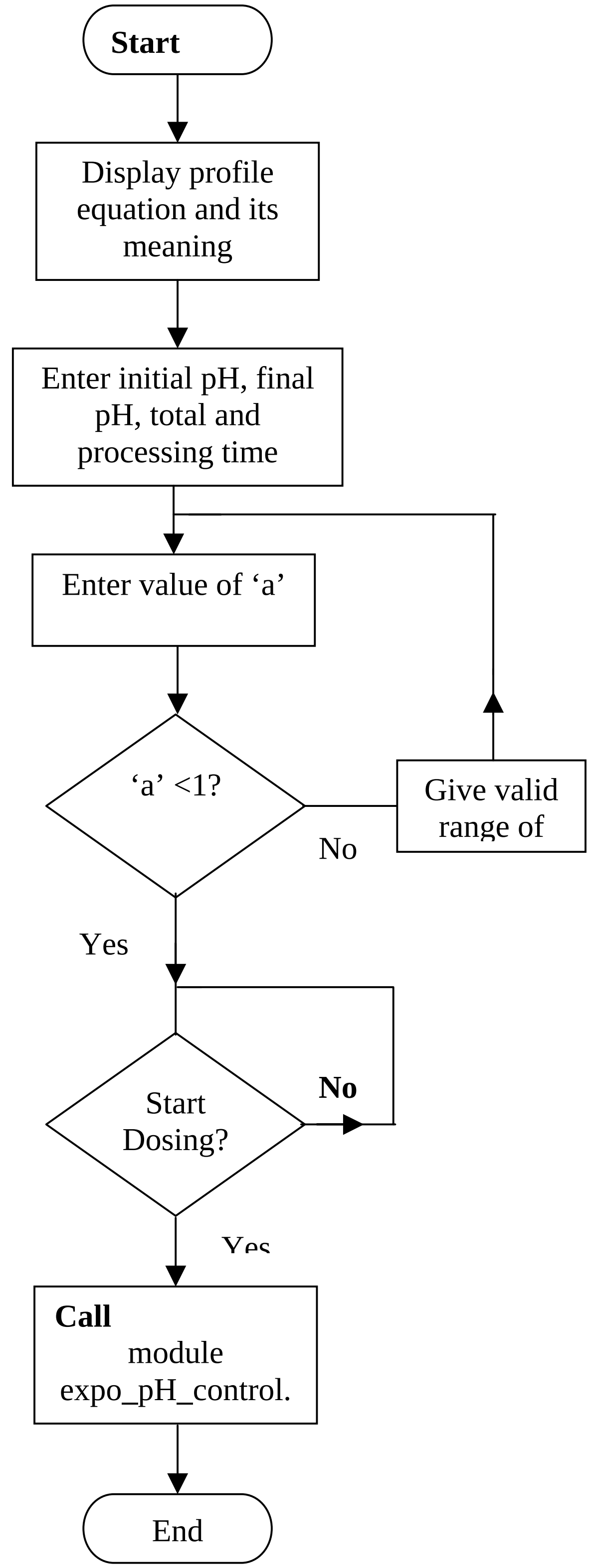


Figure 4.3 Flowchart of the pH_Expo Module

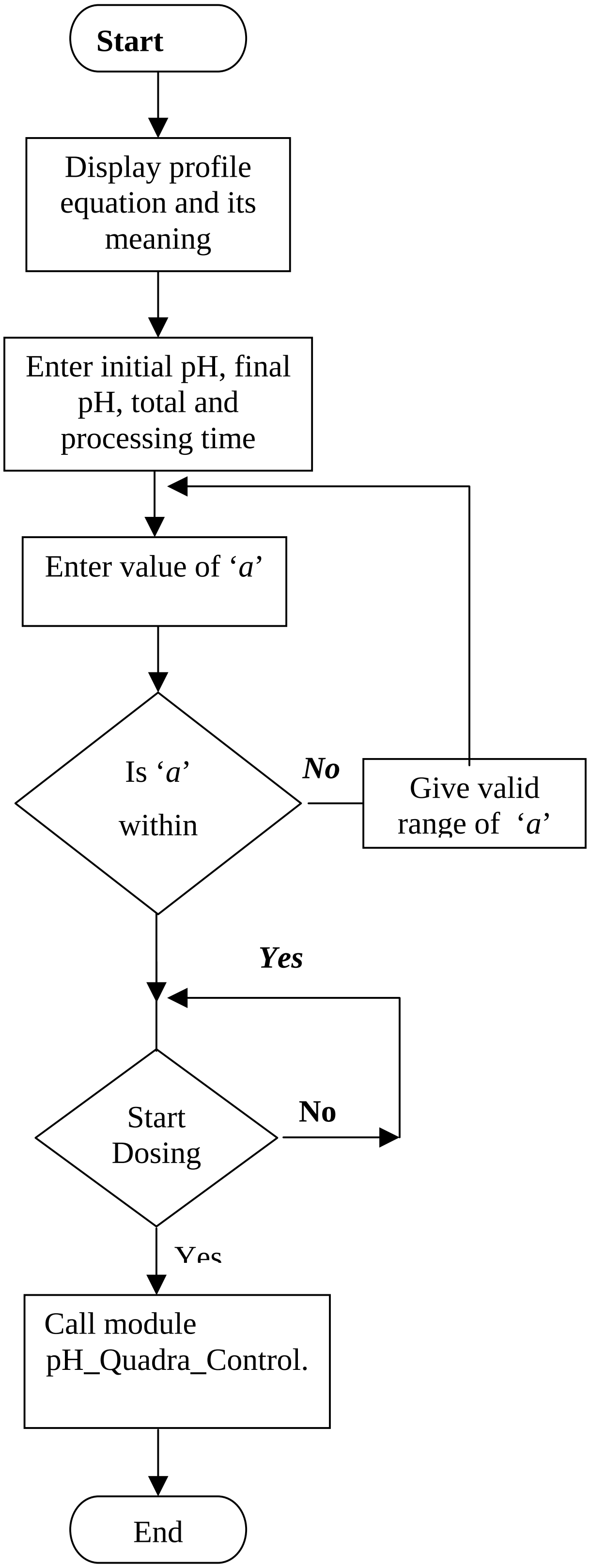


Figure 4.4 Flowchart of the pH_Quadra Module

4.2.4 pH User_Defined

In this software module, the operator is instructed how to program the controller to obtain the desired profile, as explained in Chapter 3. The program then prompts the user to enter the total processing time and subsequently to enter the pH values. Like in the other modules, a key needs to be pressed to confirm the start of the process. The corresponding flowchart is shown in Figure 4.5. The decision box ‘t=T?’ is a FOR loop, where *t* represents the sampling time (0,1,2,3…).

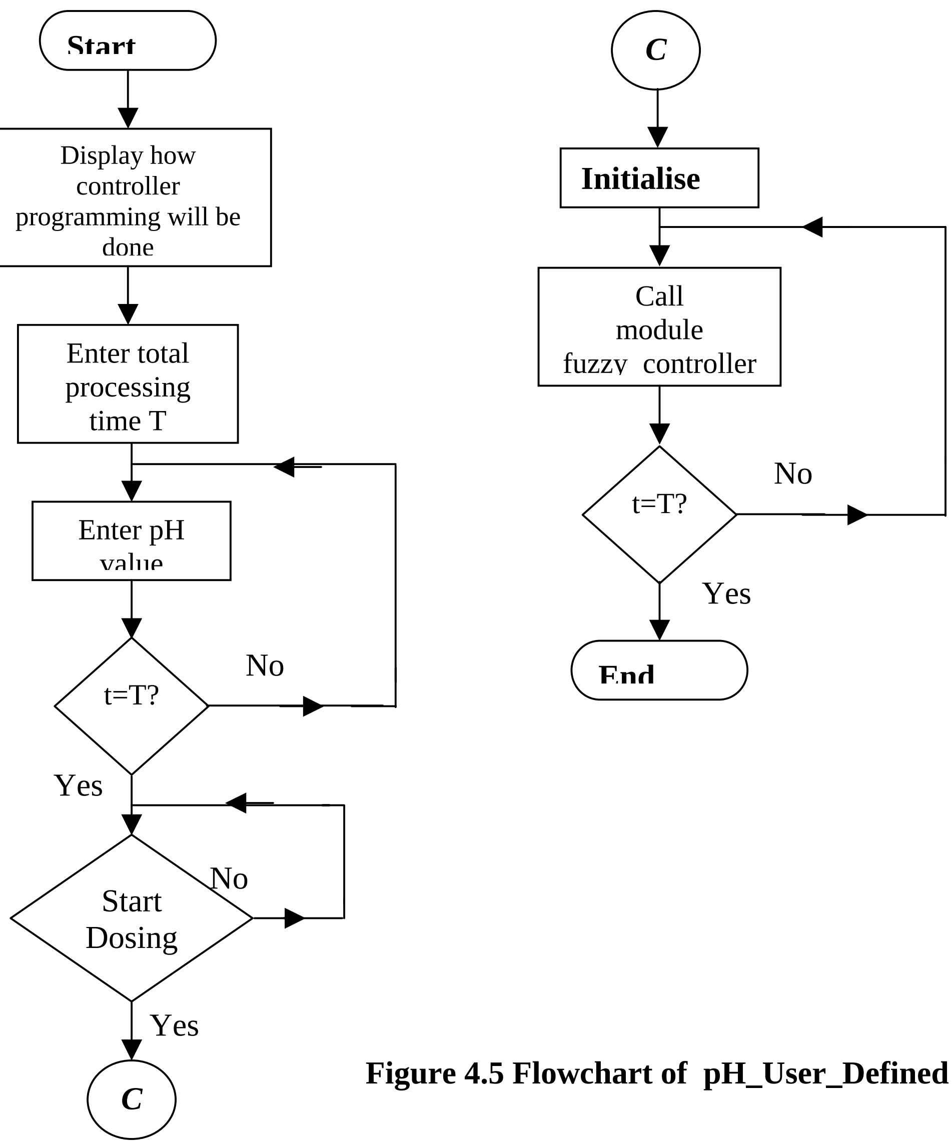


Figure 4.5 Flowchart of pH_User_Defined Module

4.2.5 pH Control for Ramp/Quadra/Expo

These modules are responsible to initialize the parallel port of the PC and to calculate the unknown value and hence the set pH. The latter is then passed to the fuzzy_controller module. As shown in the flowchart of Figures 4.6 and 4.7, this loop is continuously accessed until the total processing time is achieved. The modules also display the processing information, that is, the complete profile equation, start and final pH and the total processing time.

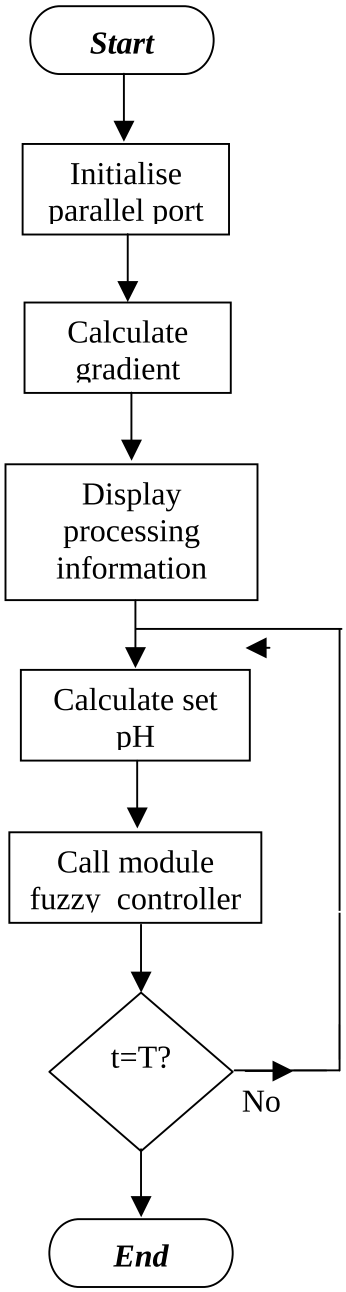


Figure 4.6 Flowchart of the Ramp_pH Control Module

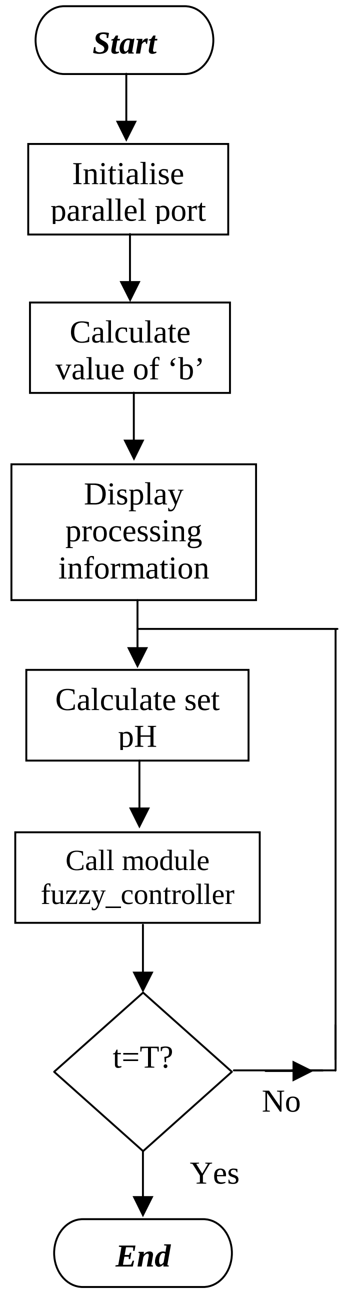


Figure 4.7 Flowchart of the Expo and Quadra_pH Control Modules

4.2.6 Fuzzy Controller

The fuzzy-controller module is responsible to coordinate the pH control operation. It receives, processes and sends information by interacting with the other subordinate modules. The steps involved are as follows:

Step1: Call for the measure_pH module, which reads the actual pH of the plant.

Step2: Display the actual and set pH values on the screen and stores these data in a file called 'fuzzy.txt'. File storage is achieved by calling the write_to_file module.

Step3: Compute the pH error and change in pH error.

Step4: Fuzzify the pH error and change in pH error. This is done by identifying within which range $e(k)$ and $\Delta e(k)$ are found using 'if' statements. Subsequently they are substituted in the corresponding equations for evaluating the degree of membership to the distinct MBFs, as explained in Chapter 3.

Step5: Perform Fuzzy inference: call for the min module, which returns the minimum from fuzzified error and fuzzified change in error. This is the aggregation step and is done for all the 49 rules.

Step6: Call for the max module which returns the maximum value from 7 numbers. This is the composition step, explained in Chapter 3.

Step7: Compute deffuzification of time by using 'if-else if' statements.

Step8: Check if deffuzified time is positive or negative and thus call the required module that would actuate the pump.

The flowchart for this module is given in Figure 4.8.

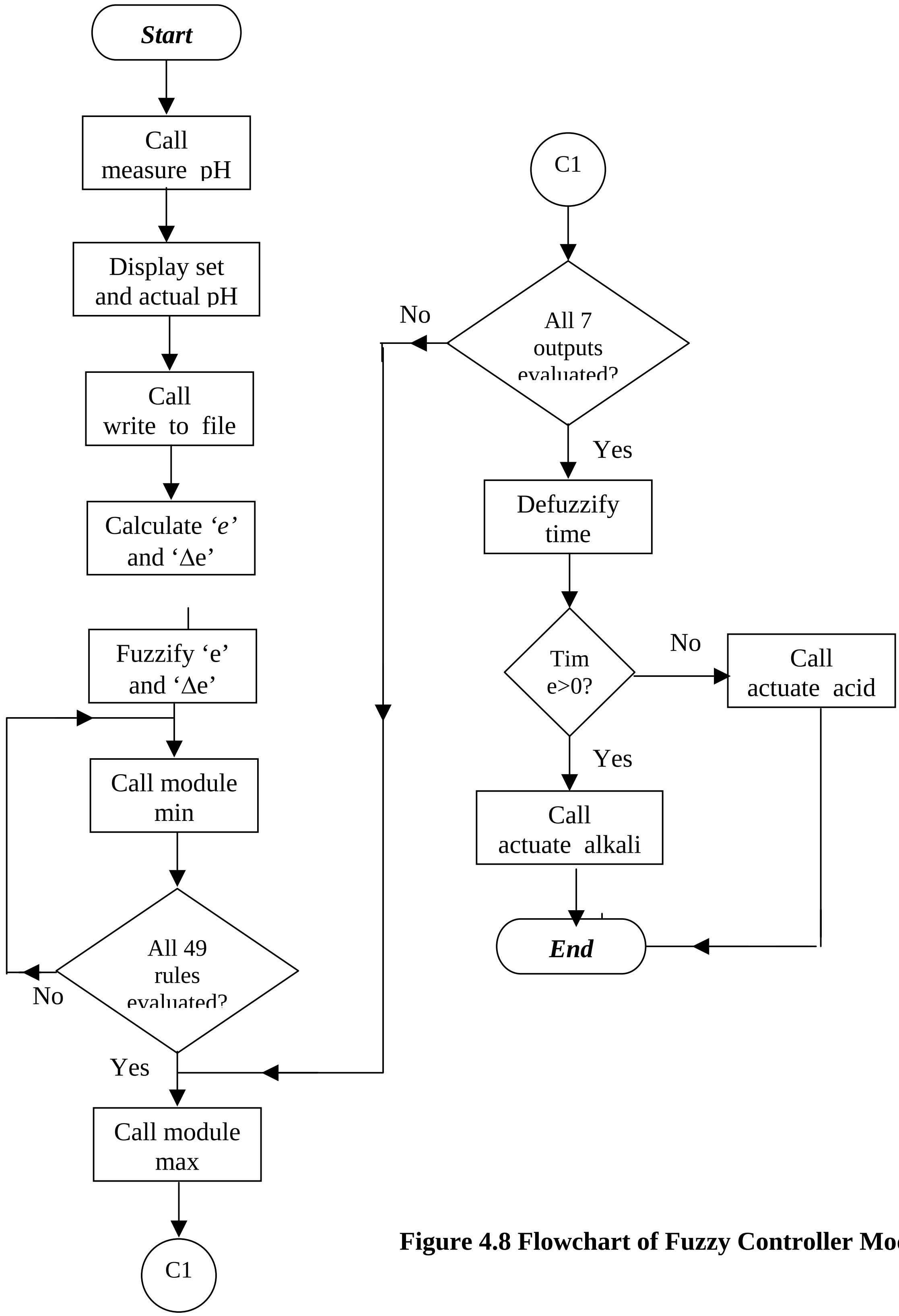


Figure 4.8 Flowchart of Fuzzy Controller Module

4.2.7 pH_Measure

The module for acquiring the pH of the bath is achieved, as shown in the flowchart of Figure 4.9.

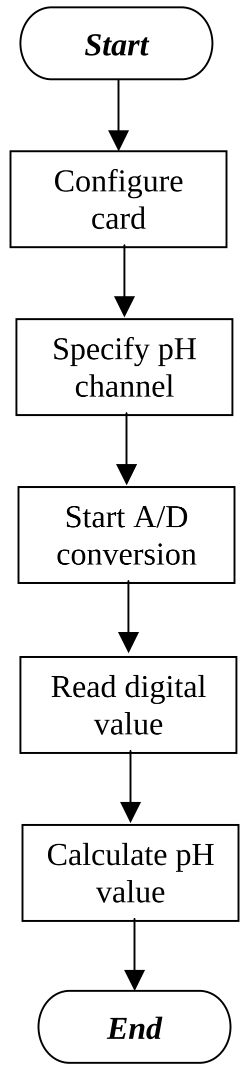


Figure 4.9 Flowchart of the pH_Measure Module

This function returns the pH value of the bath as a floating point number. The digital value is then obtained by the following equation,

$$\textbf{Digital value} = (\textbf{upper-bits} \times 256) + \textbf{lower-bits} \qquad \textit{(4.1)}$$

The voltage value is obtained by multiplying the digital value by the scale which is (10/4095). Finally, the actual pH value is computed by multiplying the voltage obtained by 1.4, since 10V corresponds to a pH of 14.

4.2.8 Write_to_File

This module stores the actual and set pH in a text file called fuzzy.txt. If the file already exists, the new pH values are appended to the end. If it does not exist, it creates and opens the fuzzy.txt file for writing.

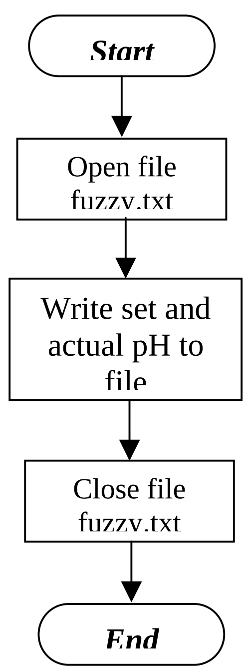


Figure 4.10 Flowchart of Write_to_File Module

4.2.9 Min, Max

As the name implies, *min* returns the minimum value of 2 numbers and *max* returns the maximum value out of 7 numbers. The flowchart for the *min* module is shown in Figure 4.11.

The *max* module uses the same principle. It compares the first number with the second number and keeps the bigger one. It then compares the retained number with the third number. Again it keeps the bigger of the two numbers. This comparison process continues for the remaining numbers. Finally it returns the biggest number.

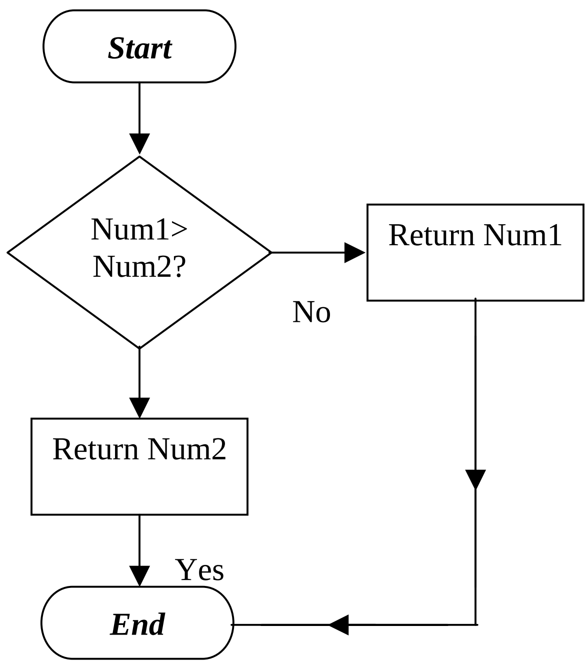


Figure 4.11 Flowchart of Min Module

4.2.10 Actuate_Acid, Actuate_Alkali

These two modules send signals to switch ON and OFF the pumps. Either of them is called at a time. First the module receives the time during which the pump needs to be activated (on-time). If the time is greater than 25 seconds, the on-time is initialised to 25 seconds. This is because the time required for the system to stabilize is 35 seconds and that sampling is done every minute.

The module then writes the required word to the PC parallel port for the relevant pump to switch ON. Next, the Delay module is called for generating the on-time delay. The pump is then switched OFF by writing 00_{hex} to the port. Finally the module checks if the actual time is equal to the final processing time. If this is the case the module exits. If not, the remaining time before the next sampling is computed and that delay is executed.

That last delay makes use of the available delay function in the C library. Note that the Delay module was developed to make provision for greater on-time duration. The available delay function of the C library can generate up to 65 seconds delay only.

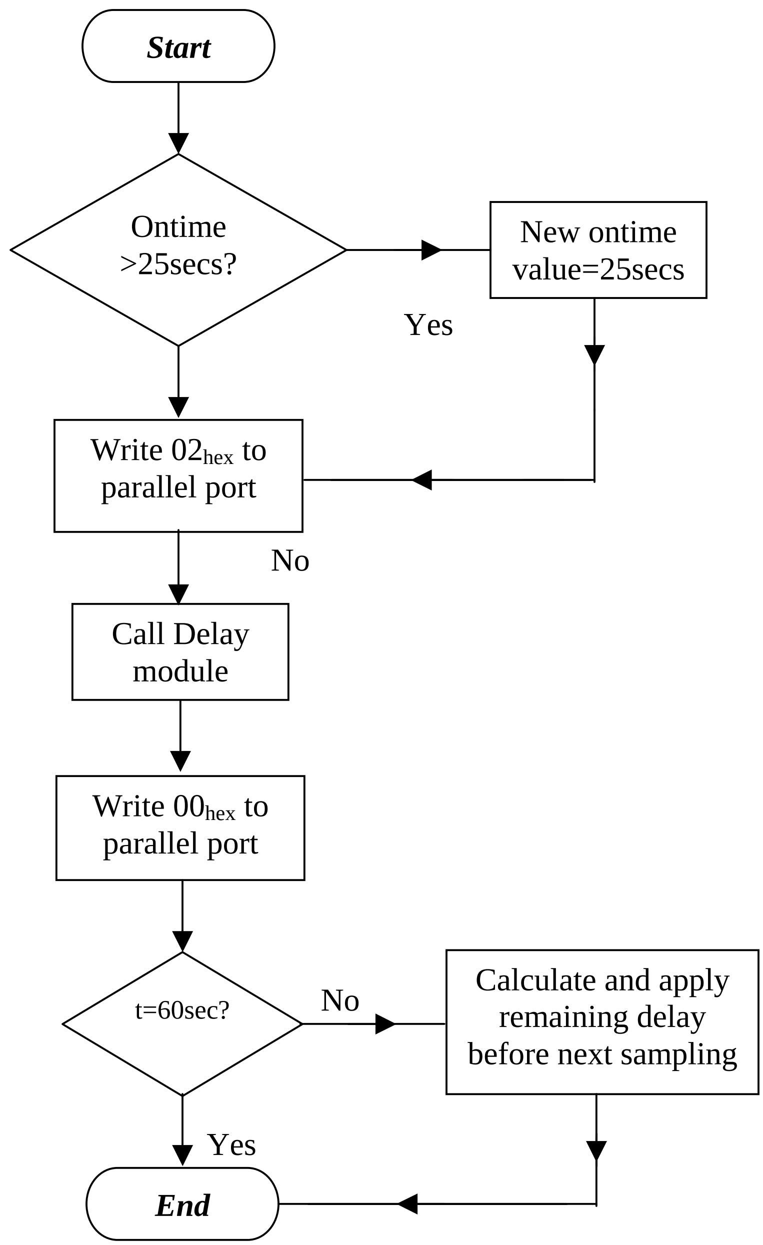


Figure 4.12 Flowchart for the Actuate_Acid Module

4.2.11 Delay

The last module is the function that generates the on-time duration. The minimum delay that it can allow is 1 second as compared to the delay function of the C library, which can generates delays in terms of milliseconds. The module records the time of the computer clock and stores it at the addresses start_time and current_time. Then it checks the following conditions:

$$(current\_time - start\_time) \leq ontime \text{ AND } (current\_time - start\_time) \geq 0$$

A new current_time is stored and the conditions re-checked. This loop continues until the conditions are no longer satisfied.

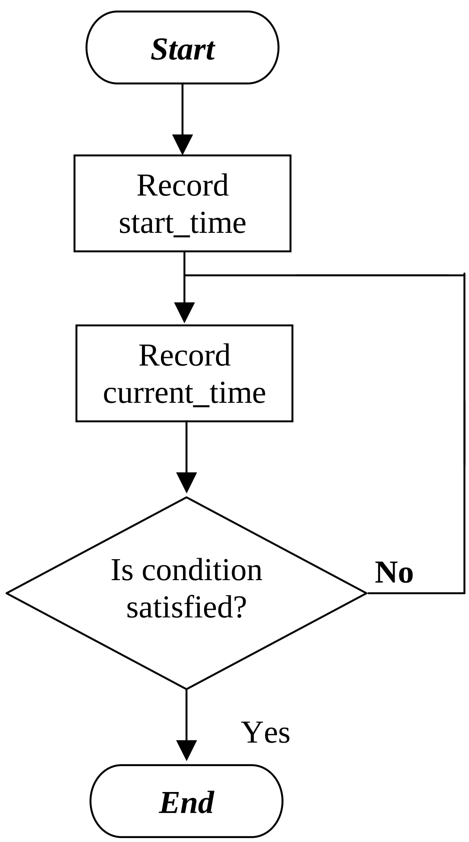


Figure 4.13 Flowchart of Delay Module

CHAPTER 5

METHODOLOGY

5.1 Dyeing Materials

Fabric

The substrate used for the experiment was a single jersey bleached cotton knitted tubular fabric. The fabric was dyed in a rope form.

Dyes

The dye employed was Sumifix Supra Brilliant Red 3BF (150%)

Auxiliaries

Anhydrous Sodium Sulphate (Na_2SO_4) was used as the electrolyte.

The alkalis were soda ash (Na_2CO_3) and liquid NaOH (50% w/w).

The acid used for controlling pH was formic acid (50%).

For fabric neutralisation after dyeing, acetic acid (100%) was used.

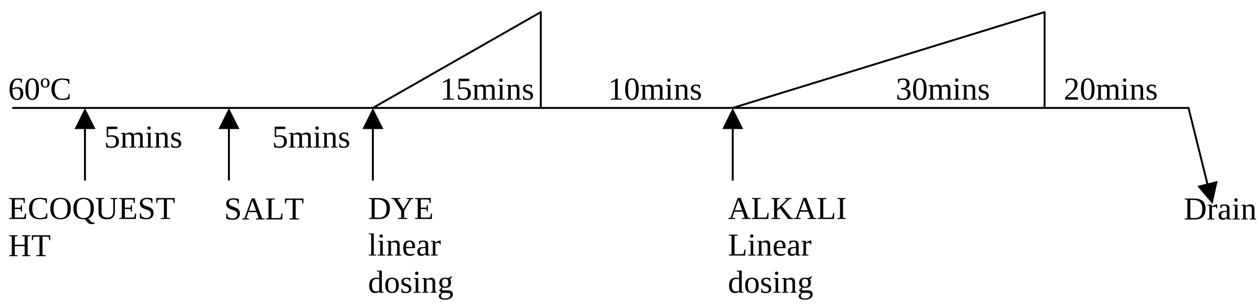
The detergent was Nishi Soap.

The sequestering agent was Ecoquest HT.

All reagent used were of laboratory grade.

5.2 Dyeing Methods

All dyeing were carried out using the Roaches M10 Jet Dyeing machine at a liquor ratio of 1:10. 3 kg samples were dyed for each batch. The dyeing profile used is as shown in Scheme 5.1



Dye: 1% on weight of fabric.
Liquor ratio is 1:10
Salt: 40g/l.
Sodium Carbonate: 5g/l.
Sodium Hydroxide: 1.6 g/l.
Starting pH: 6.5- 7.0
Ecoquest HT: 1.0g/l.

Figure 5.1 Dyeing Profile

Rinsing Procedure

- Cold rinse for 5 minutes.
- Rinse with acetic acid (2g/l) at 50ºC for 10 minutes.
- Rinse with hot water at 70ºC for 10 minutes.
- Wash with Nishi soap (1g/l) at 95ºC for 15 minutes.
- Rinse with water at 70ºC for 10 minutes.
- Cold rinse for 10 minutes.

5.3 pH Set Profiles

- **Ramp pH Profile**

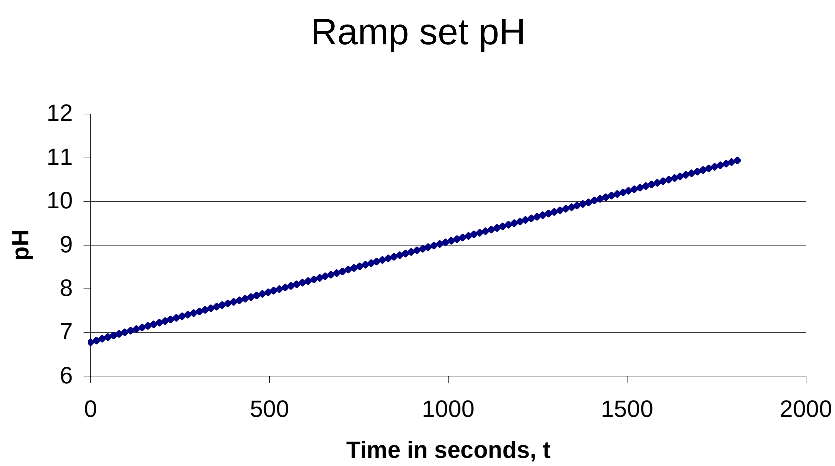


Figure 5.2 pH Ramp Profile

$$pH(t) = 0.0023t + 6.78 \quad (5.1)$$

As shown in Fig. 5.2:

Starting pH at t = 0: 6.78

Final pH at t = T: 10.92

Dosing time, T: 1800 s

The value of gradient, m, is a function of the starting and final pH and the time of dosing

o Quadratic pH Profile

With reference to Equation 3.21 (and as shown in Fig. 5.3) and using the following parameters:

$a = 9.07 \times 10^{-7}$, and dosing time, T = 1800 seconds (30 mins);

c = Starting pH at time t = 0 is 6.78

Final pH at time t = T is 10.92

The value of b = 0.00123

Quadratic Equation: $pH(t) = 0.000000907\ t^2 + 0.00123t + 6.78$. **(5.2)**

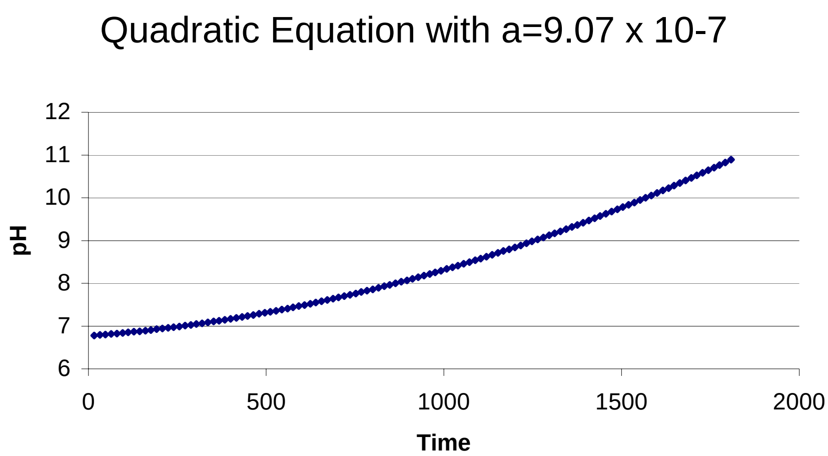


Figure 5.3 pH Quadratic Profile

- **Exponential pH Profile**

With reference to Equation 3.22 (and as shown in Fig. 5.4) and using the following parameters

a = 1, and dosing time, T = 1800 seconds (30 mins);

C = Starting pH at time t = 0 is 6.78

Final pH at time t = T is 10.92

The value of b = 991.83

Exponential Equation: $pH(t) = e^{(t/991.831)} + 5.78$ **(5.3)**

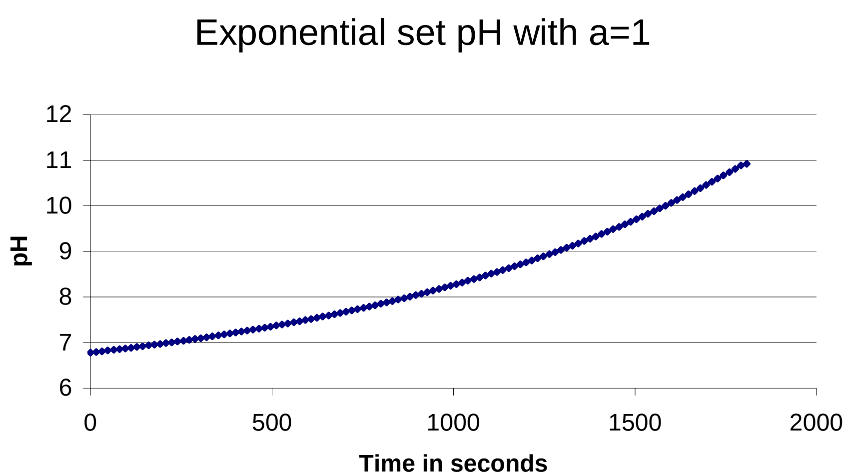


Figure 5.4 pH Exponential Profile

- **User Defined set pH: Dye Supplier's pH Profile (Linear Dosing)**

To obtain the curve shown in Fig. 5.5, a preliminary experiment was carried out, based on the total recommended volume of alkali dispensed linearly over the recommended time T, to determine the supplier's pH profile against time. For pH control, the equation generated by the curve of best fit may be used to track down the user defined pH profile. Alternatively, the pH-time coordinates thus obtained may be used as inputs to define the pH profile for subsequent dyeing processes.

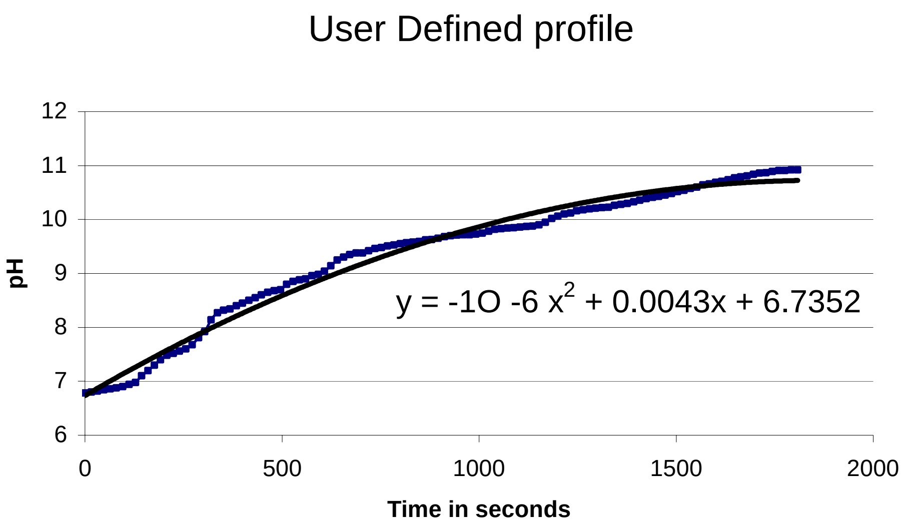


Figure 5.5 pH User-Defined Profile

5.4 Jet Dyeing Machine Parameters

1. Speed of Winch set at: 30m/min
2. The Frequency of the Main Motor Pump was set at 30 Hz and this determined the flow rate of the liquor

5.5 Determination Of Colour Yield

The amount of dye fixed onto the fabric was determined using a reflectance spectrophotometer (Datacolor SF600+). K/S values, which give a measure of the amount of dye onto the fabric, were recorded for the dyed samples together with their corresponding L*, a*, b*, DL*, DE* and percentage reflectance values, R%.

CHAPTER 6

PRELIMINARY RESULTS

6.1 EFFECT OF DYEING AUXILIARIES AND MATERIAL ON DYEBATH pH

Fig. 6.1 shows the effect of dyeing auxiliaries such as salt (Na_2SO_4), dye and the textile material on the dyebath pH at 60°C.

It is observed that for the water alone system, a pH of 11.0 is reached with a much lower amount of alkali added to the dyebath. Additional alkali is required when salt, dye and fabric is present to achieve the same final pH.

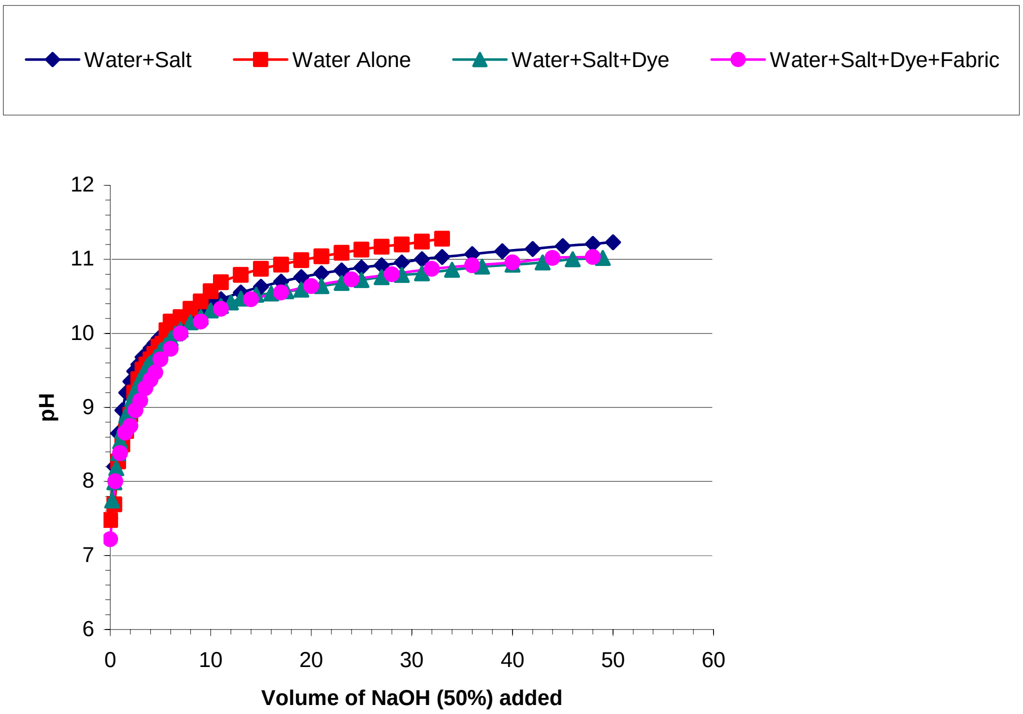


Fig. 6.1 Effect of Dyeing Auxiliaries and Material on Dyebath pH

This shows that the addition of dye, salt and fabric to the dyebath shifts the graph to the right, especially at pH values greater than 10. We also know from literature that pH varies with concentration of salt [5] and it may also change when different dyes are used. The nature of the fabric may also affect the final pH of the bath depending on the type and source of cotton fibre. For a given recommended amount of alkali for a particular dyeing process the final pH, which is very critical in the development of the right shade and for shade reproducibility, may vary from batch to batch. This makes the development of a pH controller the more important.

6.2 TUNING OF FUZZY CONTROLLER

6.2.1 Introduction

This chapter deals with the tuning of the fuzzy controller. The implementation of a working fuzzy controller normally requires expert knowledge on the operation of a process. To understand the dynamics of the dyeing system, a large number of tests/experiments need to be performed. In order to save considerable time and dyeing consumables, a mathematical model for the closed-loop system was developed and implemented on Simulink software package for simulation. This enabled good initial guesses for the fuzzy controller gains to be obtained in a relatively short time. Subsequently, experiments were performed on the dyeing system using the initial fuzzy controller gain values to further fine-tune the pH responses.

6.2.2 Modeling the Dyeing Process

To obtain the model of the process, a step input from pH 7 to pH 11 was applied to the dyeing plant by adding, at once, all the alkali and the required auxiliaries for the dyeing process at the start. The temperature of the bath was maintained at the required dyeing temperature of $60^{o}C$. The actual pH response was sampled and recorded every 500ms as shown in Fig. 6.2. No fabric was included.

From Fig. 6.2, it can be seen that it is an under-damped second order system. Such systems can be described by the following transfer function,

$$\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \qquad \textbf{(6.1)}$$

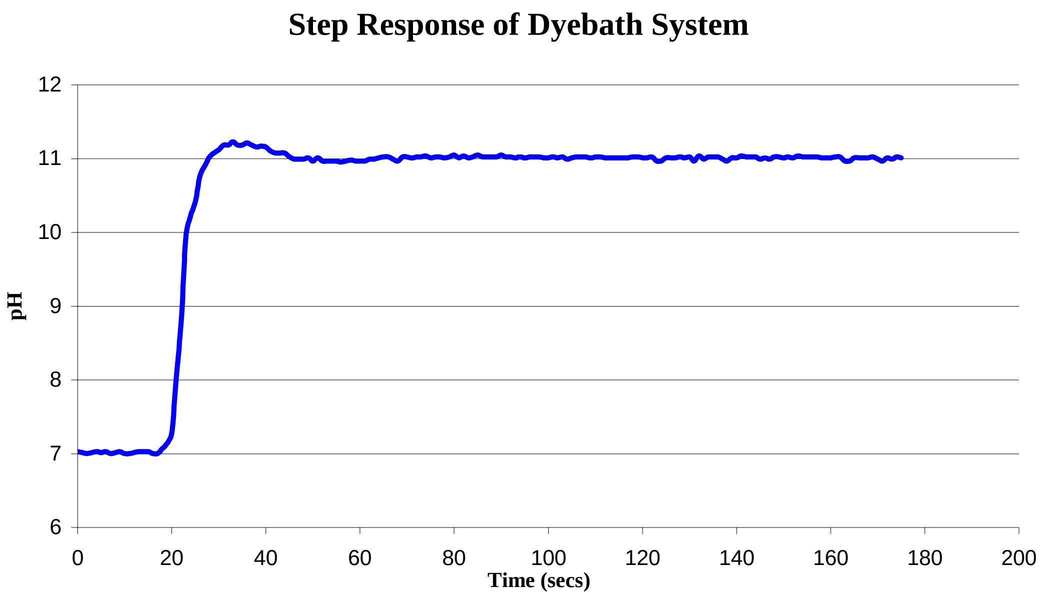


Figure 6.2 pH Response of the Dyebath

Where C(s) is the actual pH, R(s) the dosing volume, ω_n is the undamped natural frequency of the pH response and ζ the damping ratio. It should also be noted that there is a transport lag of 16 seconds in the process that need to be taken into account while modeling the system.

6.2.2.1 Calculating the Damping Ratio ζ and Natural Frequency ω_n

For an underdamped second-order system, the response c(t) is given by the following equation, [25]

$$c(t) = 1 - \exp(-\zeta\omega_n t)\left(\cos \omega_d t + \frac{\zeta}{(1 - \zeta^2)^{1/2}} \sin \omega_d t\right) \qquad \textbf{(6.2)}$$

where ω_d is the damped natural frequency.

Maximum overshoot,

$$M_p = c(t_p) - c(\infty) \qquad \textbf{(6.3)}$$

Peak time,

$$t_p = \pi/\omega_d \qquad \textbf{(6.4)}$$

From the response curve of Figure 6.1,

$$M_p = 0.2 \text{ and } c(\infty) = 11$$

Substituting M_p, $c(\infty)$, $c(t)$ and t_p in equation 5.3:

$$0.2 = 1 - \exp(-\zeta\omega_n.\pi/\omega_d)\left(\cos \omega_d.\pi/\omega_d + \frac{\zeta}{(1-\zeta^2)^{1/2}} \sin \omega_d.\pi/\omega_d\right) - 11$$

Upon simplification,

$$0.2 = -10 + \exp[(-\sigma/\omega_d)\, \pi]$$

But,

$$\sigma = \zeta\omega_n \qquad \textbf{(6.5)}$$

$$\omega_d = \omega_n(1 - \zeta^2)^{1/2} \qquad \textbf{(6.6)}$$

Therefore,

$$0.2 = -10 + \exp[\, (-\zeta\omega_n\, \pi) / \omega_n(1 - \zeta^2)^{1/2}\,]$$

$$\zeta = \left((\ln 0.2)^2 / [\, \pi^2 + (\ln 0.2)^2\,]\right)^{1/2}$$

$$= 0.594$$

Now, $\omega_n = \pi / t_p\, (1 - \zeta^2)^{1/2}$ **(6.7)**

From the response curve, t_p = 18 secs

Therefore, ω_n = 0.217

Hence, the transfer function of the system is given by:

$$\frac{pH(s)}{V(s)} = \frac{0.047}{s^2 + 0.258s + 0.047} \qquad \textbf{(6.8)}$$

In this system therefore, the input V(s) is the volume of injected alkali and the output pH(s) is the pH of the bath.

6.2.3 Modeling the Dosing Pump

The dosing pump is modeled as a linear element. It converts the fuzzy controller output, i.e. time, into a volume. For example, the pump can be calibrated such that it provides a flow of 0.1mL per second. Hence in the simulation, the dosing pump is simply represented by a gain, k_{DP}. This gain is also adjustable manually on the pump. However, it can take only 3 values which are: 0.1, 0.2 and 0.3. This is because the minimum chemical the chosen pump can inject is 0.1mL per stroke. And the maximum chemical it can inject in 1 second is 0.3mL, when it is at its maximum flow rate capacity.

6.2.4 Modeling the Control System and Tuning by Simulation

The block diagram of the simulated system in Simulink is as shown in Figure 6.3. It is desirable to have a response that has the following characteristics.

1. No oscillations
2. Steady-state error to almost zero
3. Minimum settling time

The final gains were chosen such that the response met the above-mentioned characteristics. The oscillations could be removed, as well as minimizing the settling time by simply adjusting k_e, $k_{\delta e}$, k_u and k_{DP}. However, it was not possible to remove the steady-state error. Therefore, an integrator was introduced at the output of the fuzzy controller. Further gain adjustments were made and the steady-state error was reduced to about 0.03.

This error was quite noticeable when comparing the reference (set) and the response (actual) curves. Hence, a second integrator with a gain k_i, was combined with the error signal and fed to the fuzzy controller in the model. The pH error was integrated, summed to that same error and then input to the fuzzy controller.

After several simulations, the final simulation gains were as follows:

- k_e = 0.02
- $k_{\delta e}$ = 0.02
- k_u = 2
- k_{DP} = 0.1
- k_i = $1x10^{-4}$

6.2.5 Fine Tuning the Implemented System

The implemented system was fine-tuned using the above gains as a starting point. After several trials, the gains of the implemented system were set as follows:

- k_e = 0.008
- $k_{\delta e}$ = 0.002
- k_u = 2
- k_{DP} = 0.1
- k_i = $1x10^{-5}$

k_i

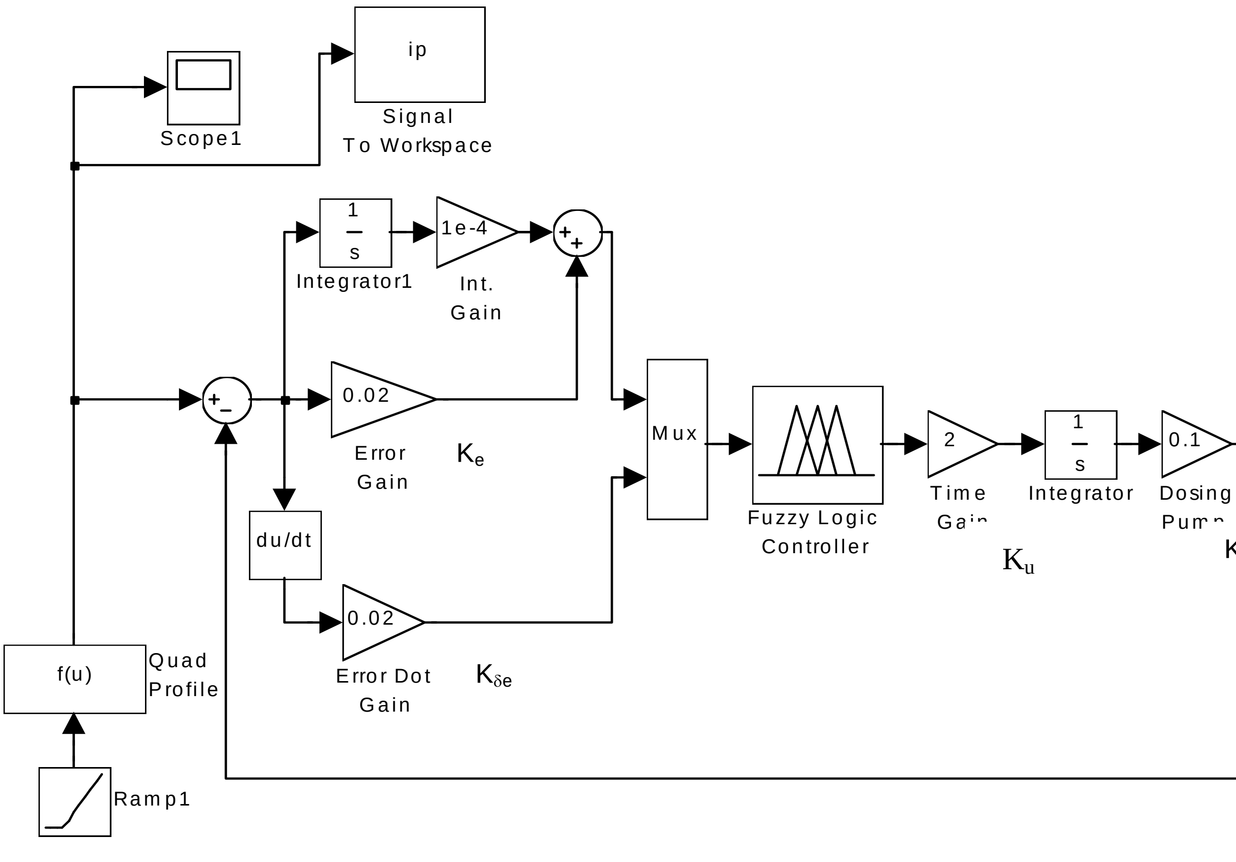


Fig. 6.3 Block Diagram of the Simulated System in S

6.2.6 Other Modifications

Two further modifications were brought to the real life system after simulation. Two integrators were included in the software and the MBF of the error was changed.

INTEGRATOR

To discretise the continuous time integrator 1/s using the z transform, the Bilinear Transformation was applied. In this transformation, the Laplace operator 's' was replaced by,

$$s \leftarrow \frac{2(1-z^{-1})}{T_s(1+z^{-1})} \qquad \textbf{(6.9)}$$

Where T_s is the sampling time.

Therefore,

$$\frac{y(t)}{u(t)} = \frac{T_s(1+z^{-1})}{2(1-z^{-1})}$$

where, y(t) and u(t) are the output and the input of the integrator respectively.

Upon simplification,

$$y(t) = \frac{T_s[u(t) + u(t-1)] + 2u(t-1)}{2} \qquad \textbf{(6.10)}$$

Equation (6.10) is the integrator algorithm used in this project.

MBF

The new MBF for the error is shown in Figure 6.4. The widths of the MBFs were reduced in order to increase the sensitivity of the controller.

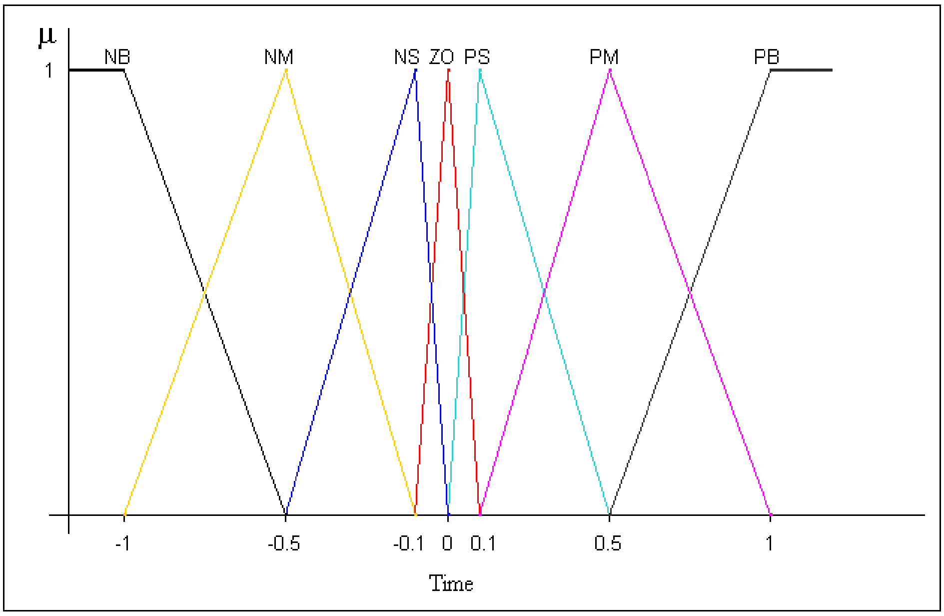


Figure 6.4 New MBF for Error Input

6.2.7 Fine-Tuning Results

Simulation and experimental results for the four different proposed pH profiles are shown in Figures 6.5 to 6.12. The initial and final pH values were 7.0 and 11.0 respectively for all the tested profiles. Note that on the ***simulation*** response curves (Figs. 6.5, 6.7, 6.9, 6.11), pH 7.0 is represented by 0 and pH 11.0 by 4. The blue line represents the reference pH and the red line represents the actual pH. In experimental results (Figs. 6.6, 6.8, 6.10, 6.12), the thick black dotted lines represent the trend of the actual pH of the implemented system.

Also, during fine-tuning (implemented system), the pH profile was tracked down for water only in the system. Under true dyeing conditions the actual pH profile followed similar trends to the water alone system (as described in Section 6.1). The bath was heated to the required temperature, i.e. 60^{o}C, and the set pH profile followed was for water system only, i.e., no salt, dye and fabric were included in the experiment.

Significant differences in performance of the simulated model and the actual process were observed. In all simulation results, the process pH tracks the reference profile with negligible error, while in the actual implemented system a large difference between set and observed pH values was noted, especially, for the larger values of reference pH. It should be noted that the model of the dyeing process derived in Section 6.2.2 is a linearised second order version of the plant's characteristic as shown in Eq. 6.1. Non-linearities and time-varying parameters of the dyeing plant have not been taken into consideration in the modeling process, thus resulting in an idealized simulation response.

In the experimental tests, the largest deviations in actual pH are of the order of 0.6 and are observed mainly in the quadratic profile (Fig. 6.10), where the time rate of change of the reference is highest, compared to the remaining profiles. Furthermore, it is noted that the deviations become larger, when the reference pH exceeds 9. To correct for such tracking errors, the fuzzy controller gain, k_e, was varied on line according to the reference pH values. The reference pH profile was divided into a minimum of three segments, and a different controller gain was applied for each segment, so that the gain increases with pH. The results for this adaptive fuzzy control scheme are shown in Figs. 6.13 to 6.15, for the quadratic pH profile, which is among the most difficult to track. The improvement in tracking error was significant between pH 9 and pH 10, compared to the previous non-adaptive fuzzy controlled systems.

6.2.7.1 Ramp Profile

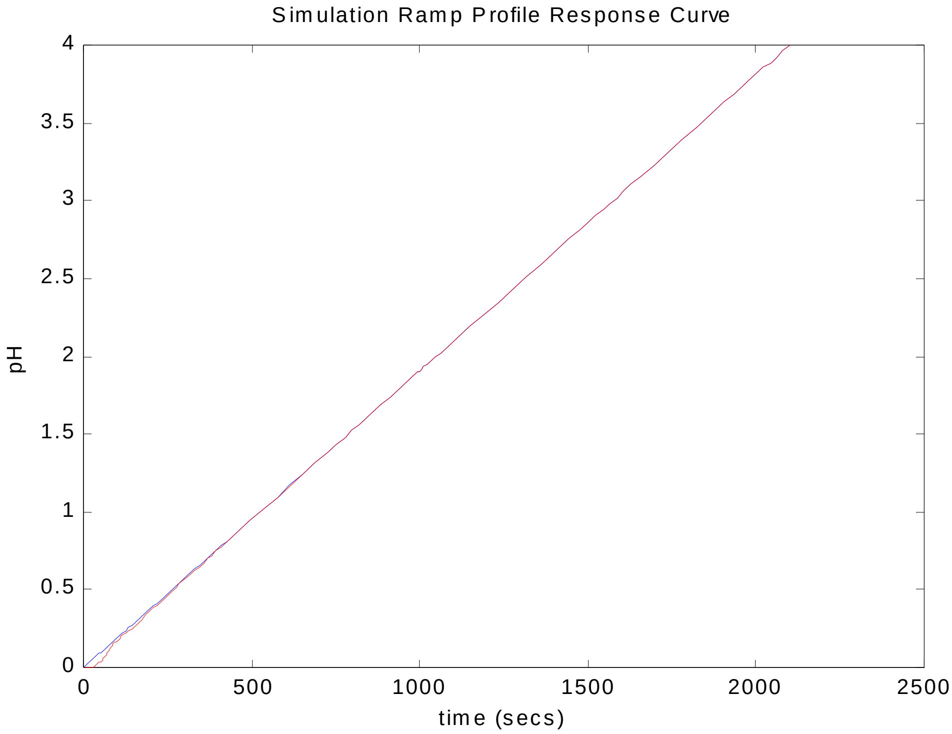


Figure 6.5 Ramp Profile Simulation Results

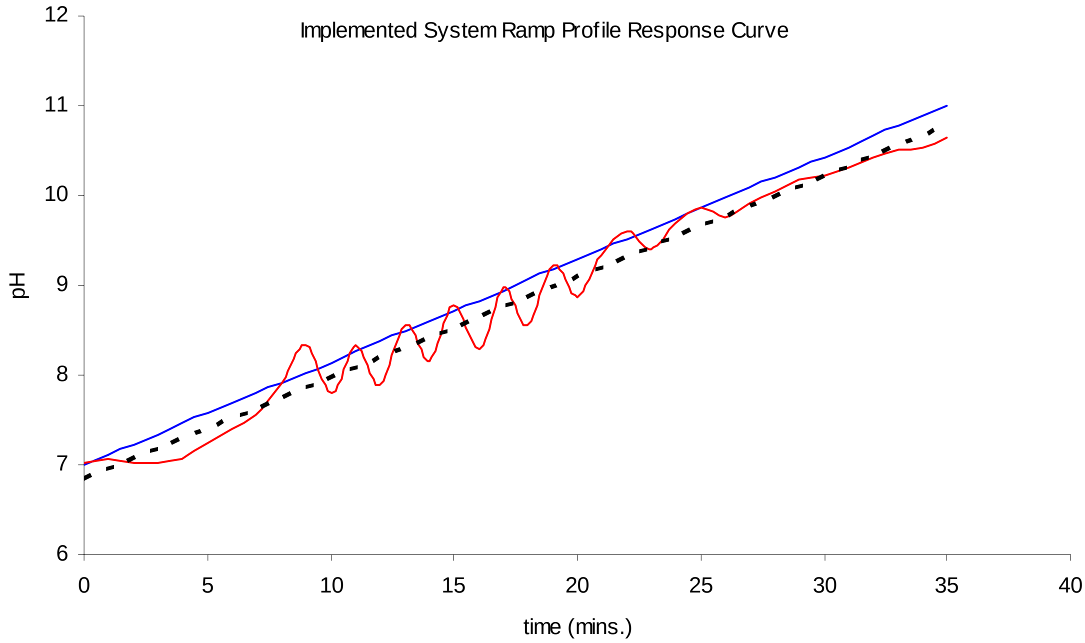


Figure 6.6 Ramp Profile Implemented System Results

6.2.7.2 Exponential Profile

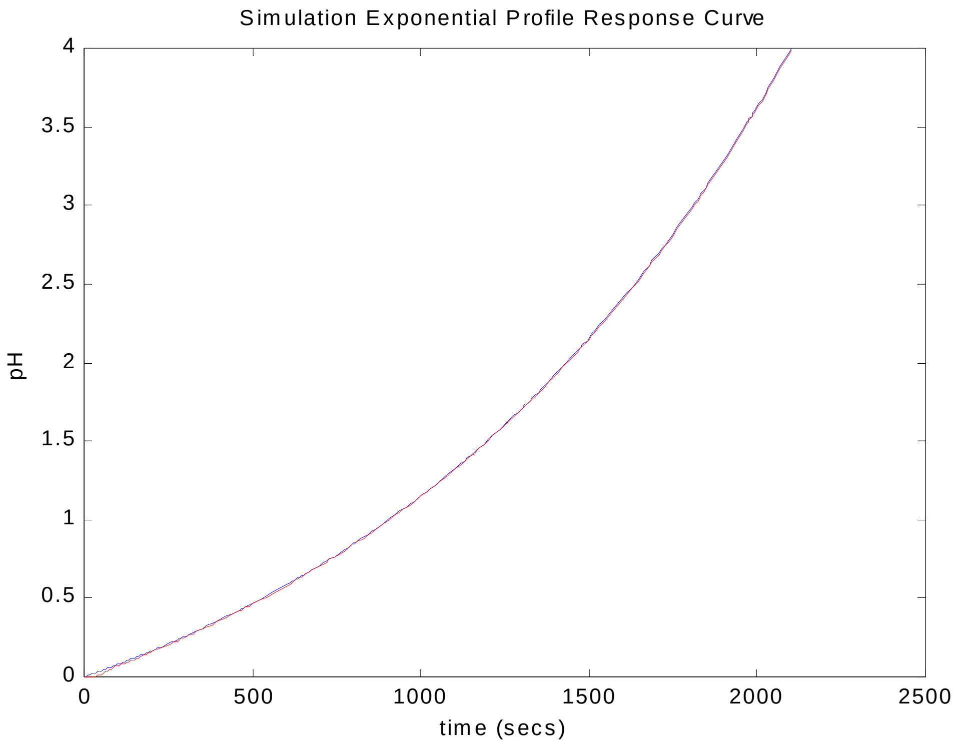


Figure 6.7 Exponential Profile Simulation Results

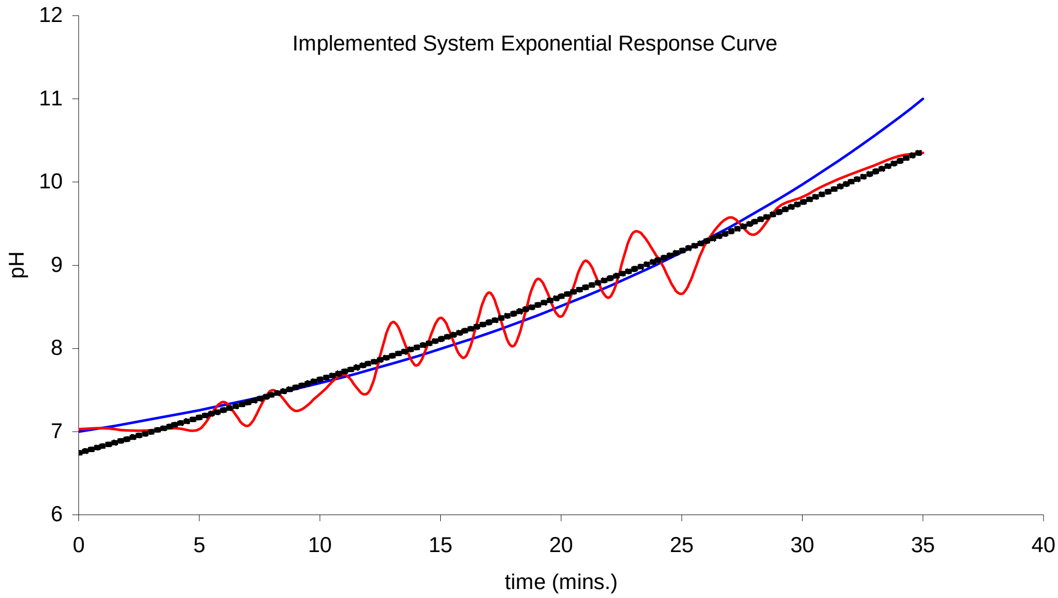


Figure 6.8 Exponential Profile Implemented System Results

6.2.7.3 Quadratic Profile

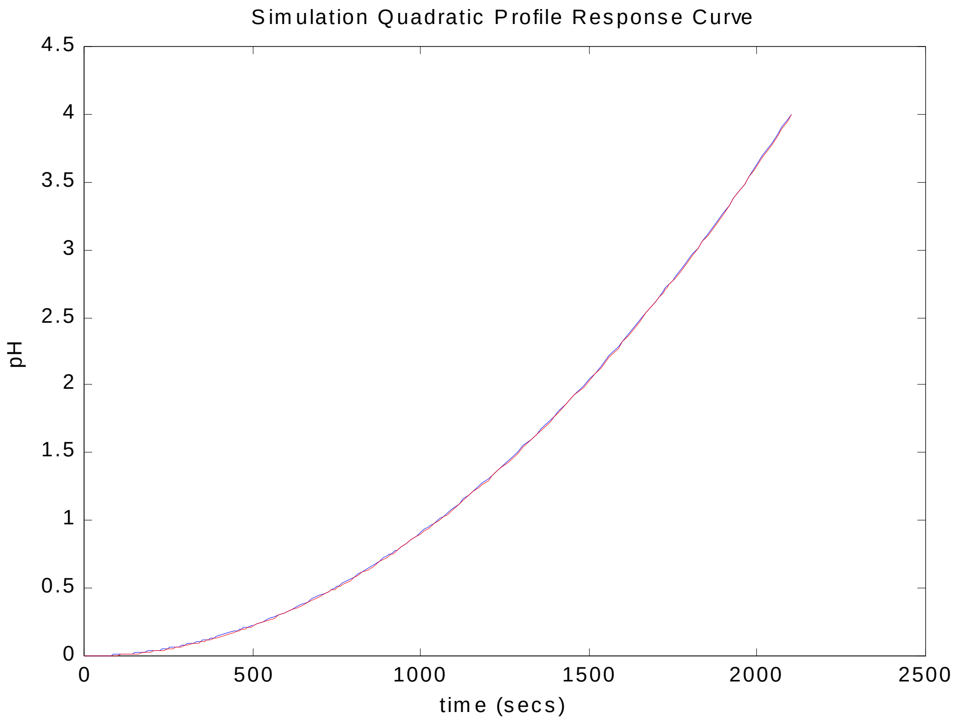


Figure 6.9 Quadratic Profile Simulation Results

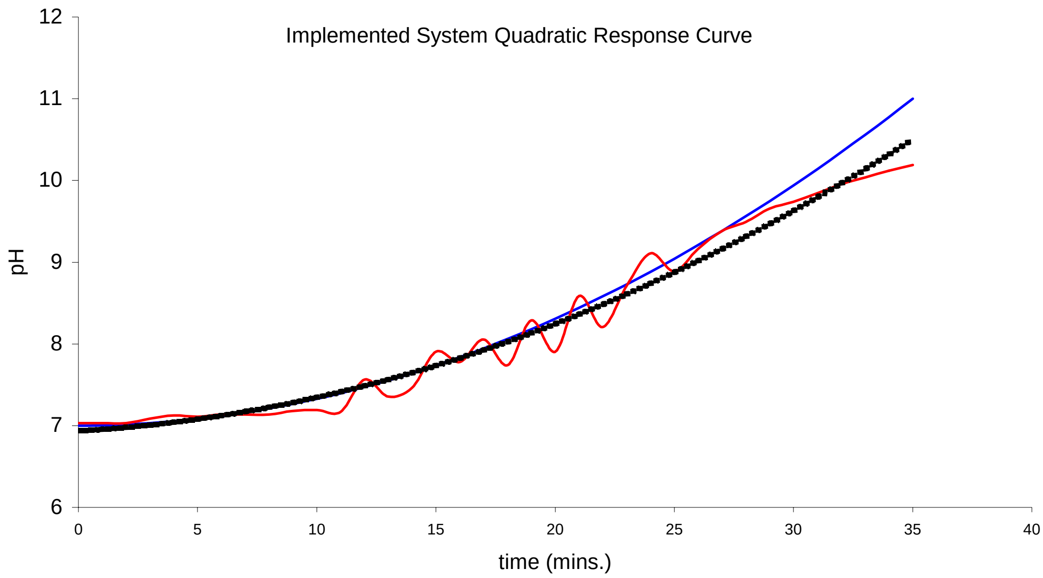


Figure 6.10 Quadratic Profile Implemented System Results

6.2.7.4 User-Defined Profile

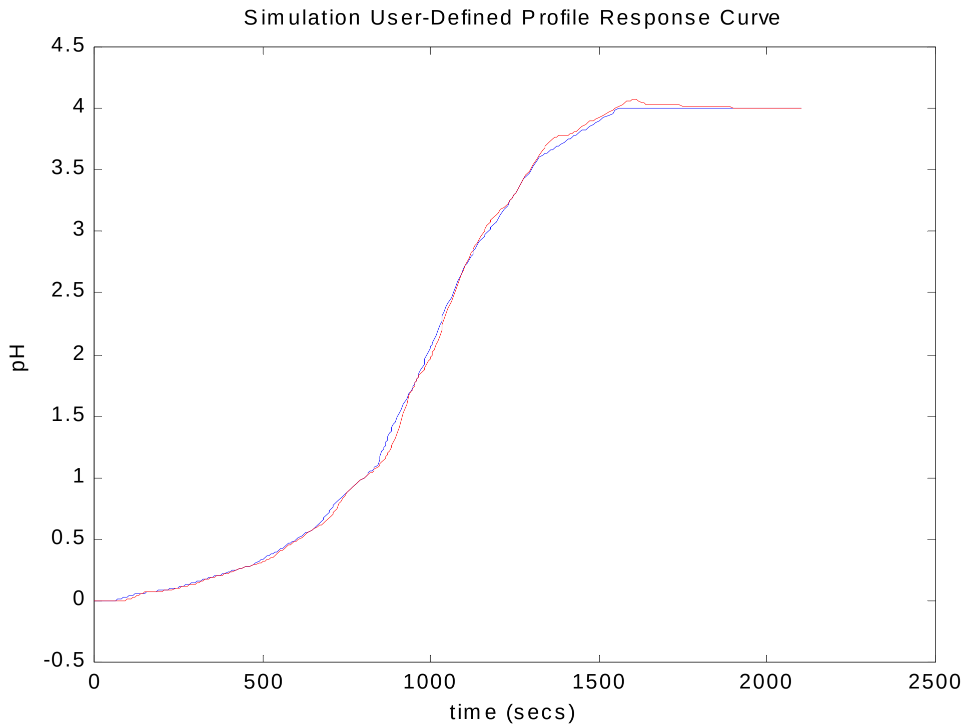


Figure 6.11 User-Defined Profile Simulation Results

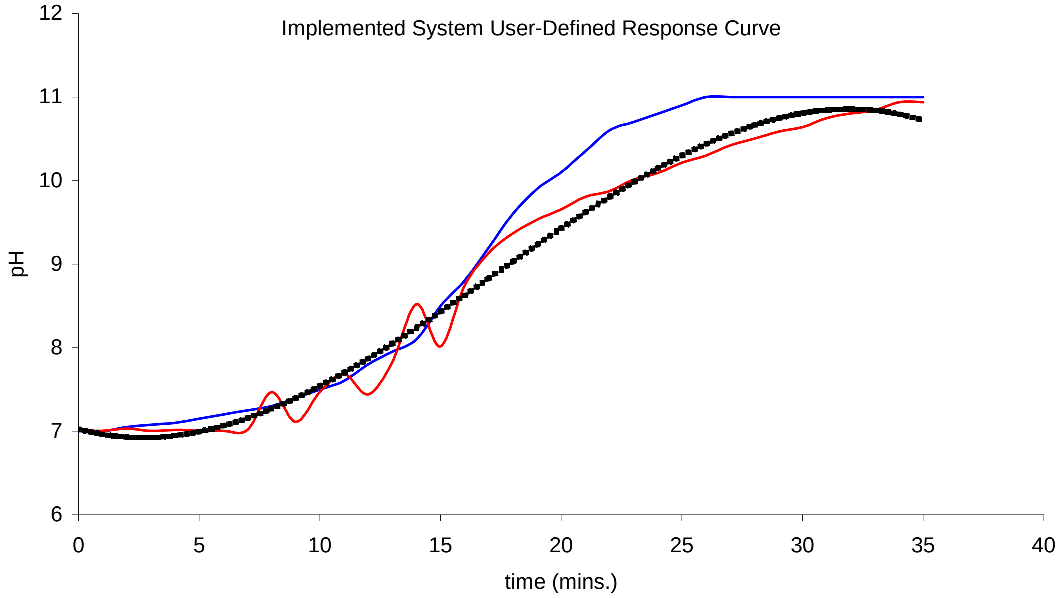


Figure 6.12 User-Defined Implemented System Results

6.2.7.5 Quadratic Profile For Adaptive System

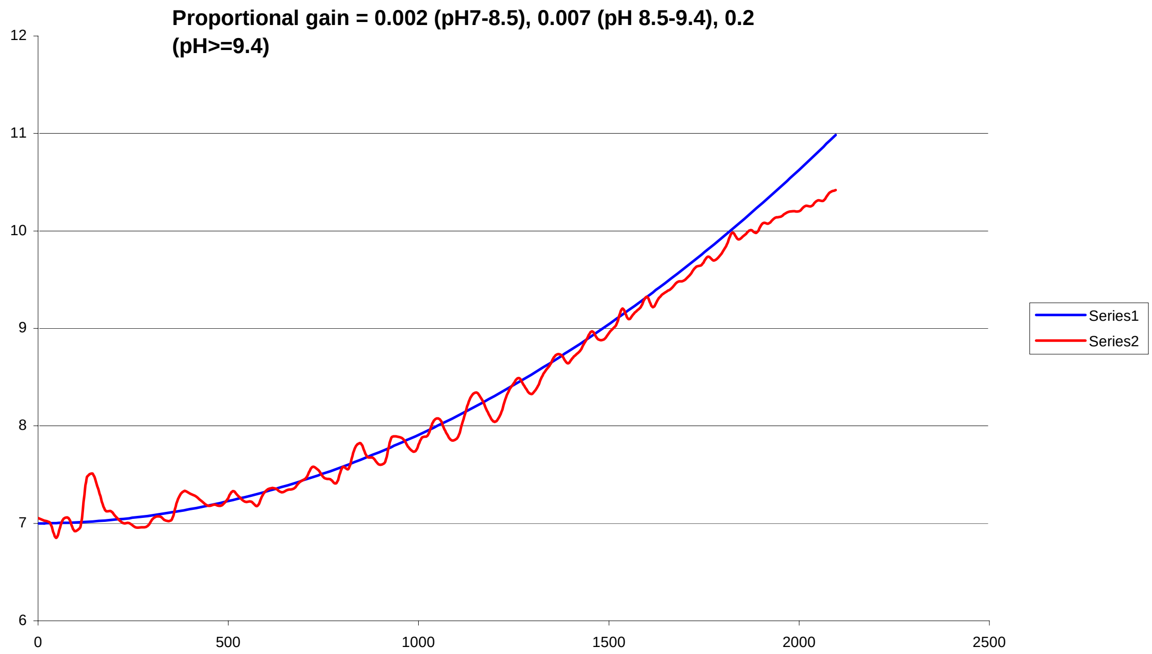


Figure 6.13 Quadratic Profile For Adaptive System Results I

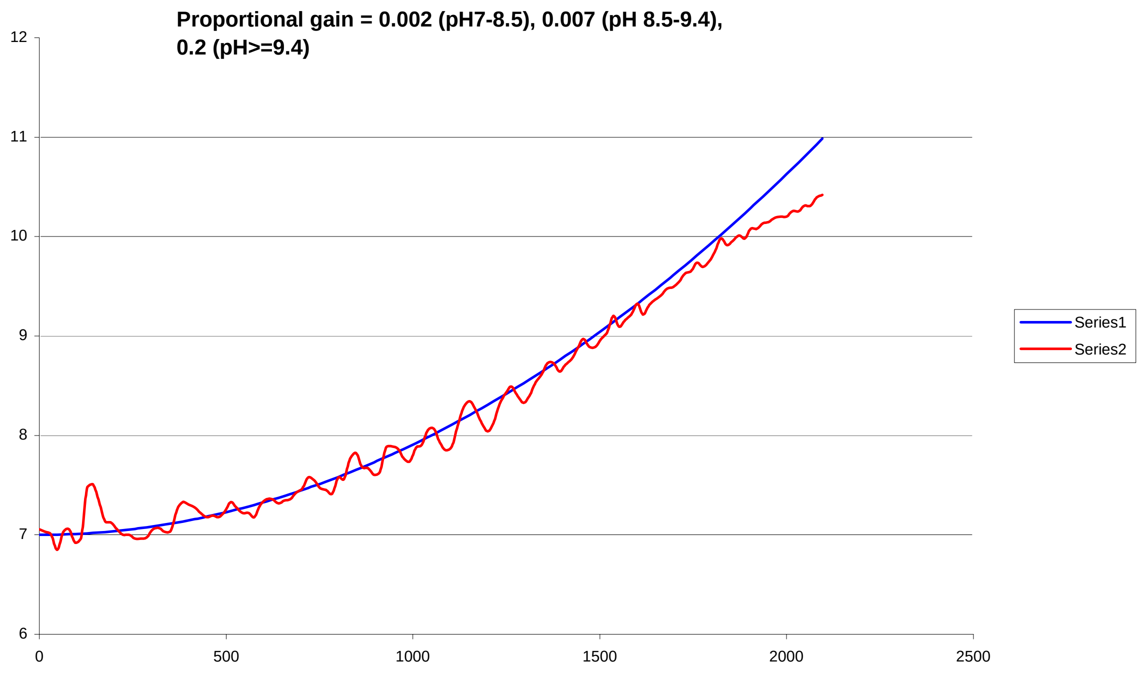


Figure 6.14 Quadratic Profile For Adaptive System Results II

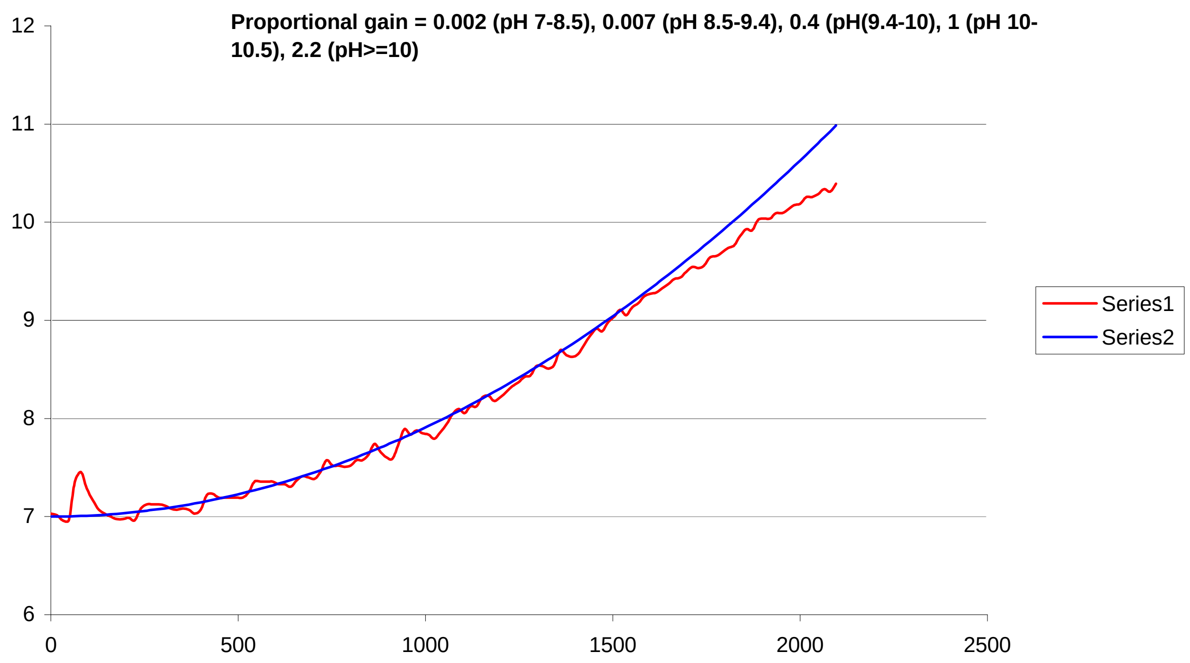


Figure 6.15 Quadratic Profile For Adaptive System Results III

CHAPTER 7

RESULTS AND DISCUSSIONS

7.1 Fine-Tuned Fuzzy Controller Performance Under Normal Dyeing Conditions

The fined-tuned fuzzy controller described in Section 6.2 was tested with fabric and auxiliaries in the dyebath, representing normal industrial dyeing conditions. Figures 7.1 (a) to 7.4 (a) show the performance of the fuzzy controlled system for the typical pH profiles described in Chapter 6 (Figs. 7.1(a), 7.2(a), 7.3(a) and 7.4 refer to the results of Expt. 1 and Figs. 7.1(b), 7.2(b), 7.3(b) refer to Expt.2). Comparison with Figs. 6.11, 6.12, 6.13, respectively, show that the presence of fabric and auxiliaries does not significantly affect the tracking performance of the control system (*except for the user-defined profile (Figs. 7.1(a) & (b)), where the rate of change of the set pH is much higher, compared to the other profiles*). In fact, the largest deviations in actual pH remain around 0.4-0.5. They are observed mainly for the quadratic and exponential pH profiles at pH values greater than 10.0 (Figs. 7.2, 7.3 (a) & (b) and where the time rate of change of the reference pH is highest, compared to the remaining profiles.

To make up for the pH error at the final stage of the dyeing process, the dosing pumps were bypassed, and the dyebath was dosed manually when the set pH value exceeded 10.0. The corresponding response plots are shown in Figs. 7.1 (a) to 7.4(a). Manual dosing ensures that the final value of dyebath pH matches the reference (set) value.

A number of factors are responsible for the tracking error in the fine-tuned controller. The acid/ alkali concentrations used in the experiment, especially for the alkali, require that a relatively large dosing volume is required to achieve significant pH change of the dye bath, at pH values greater than 10.0. Besides, increasing the gain of, k_e, of the controller does not cause significant improvement in the tracking response, since the fuzzy controller is already working near its maximum dosing volume (based on the pump set flow rate) at large values of k_e.

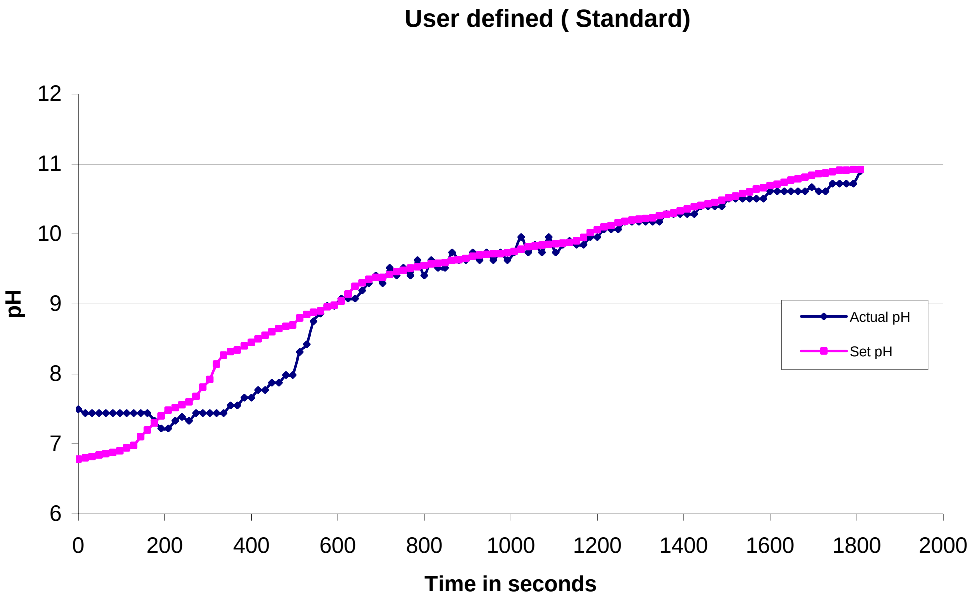


Fig. 7.1(a) User Defined (Standard) pH Profiles (Actual and Set)

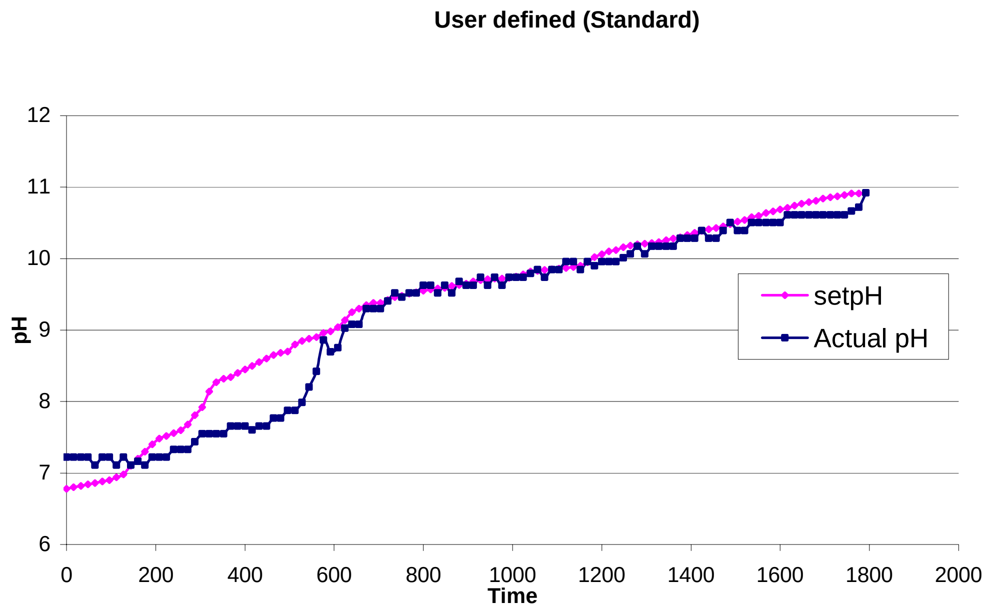


Fig. 7.1(b) User Defined (Standard) pH Profiles (Actual and Set)

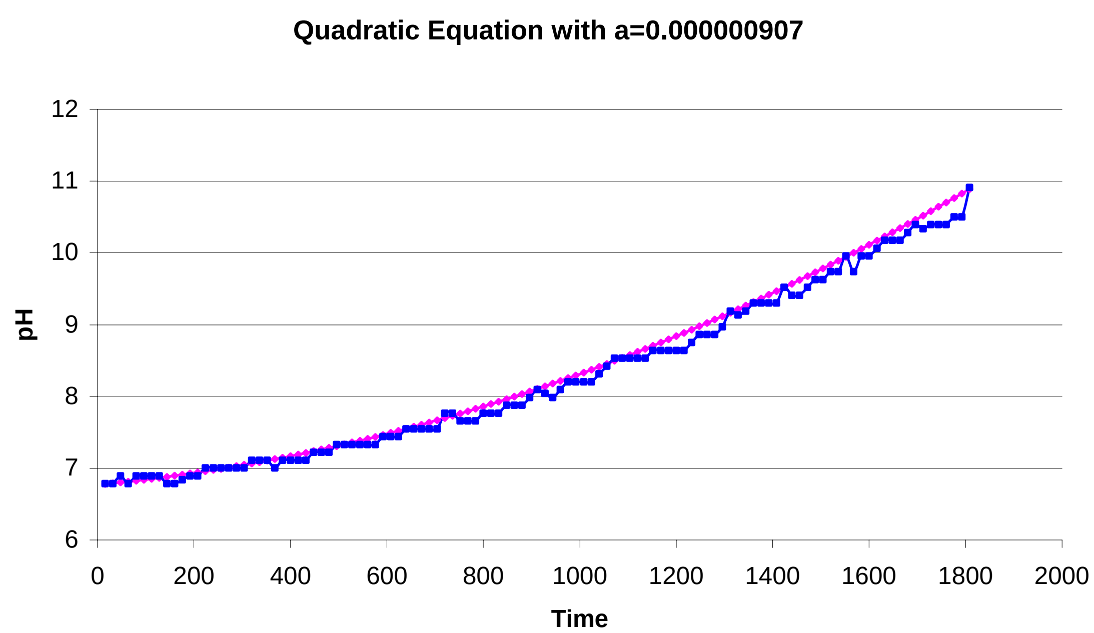


Fig. 7.2(a) Quadratic pH Profiles (Actual and Set)

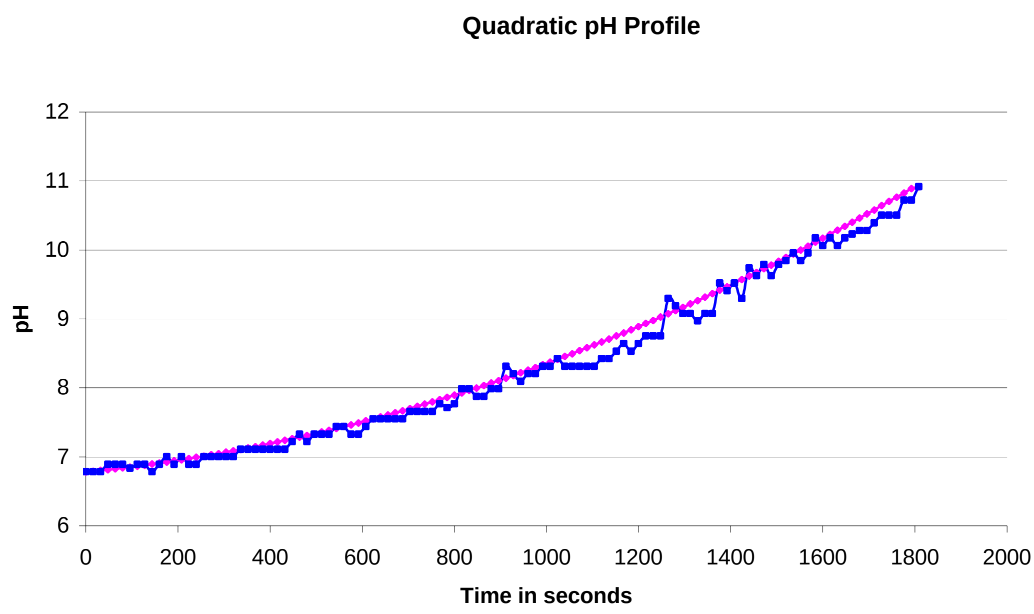


Fig. 7.2(b) Quadratic pH Profiles (Actual and Set)

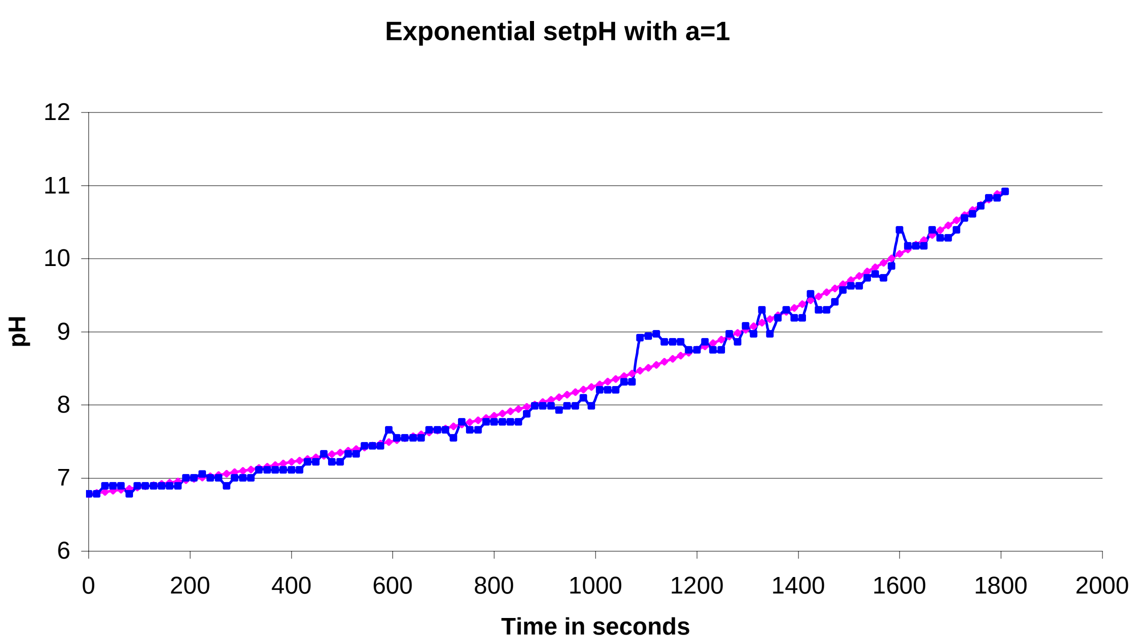


Fig. 7.3(a) Exponential pH Profiles (Actual and Set)

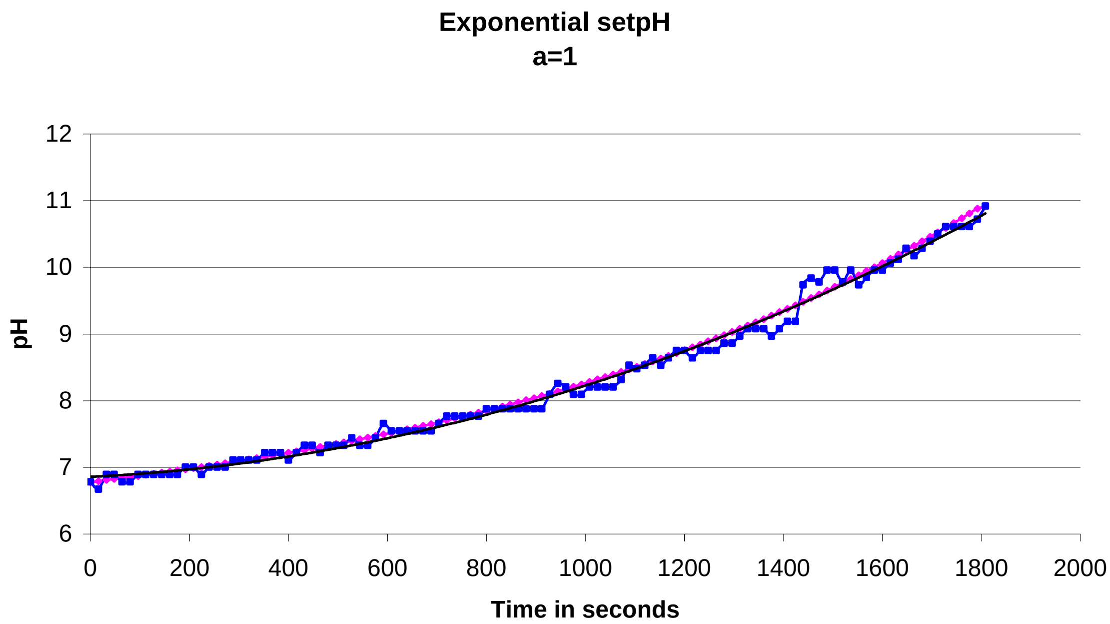


Fig. 7.3(b) Exponential pH Profiles (Actual and Set)

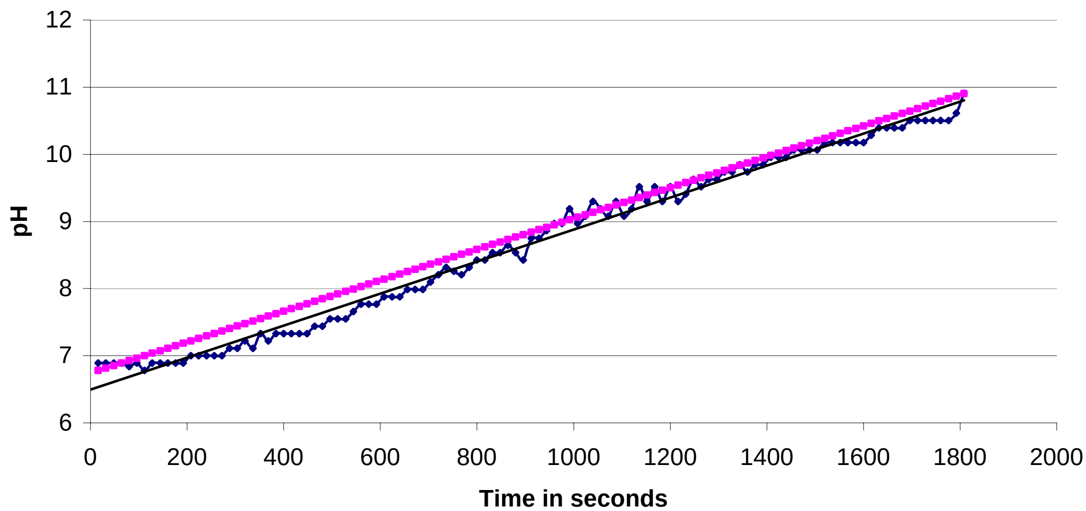


Fig. 7.4(a) Ramp pH Profiles (Actual and Set)

7.2 Results of Reflectance Spectrophotometric Measurements

For all the samples tested, the readings have been averaged out over two sets of dyeing. The standard sample was taken as the one that has been dyed using the supplier's ***linear dosing profile*** (volume of alkali against dosing time) that was subsequently transformed into a user-defined set pH profile.

Similar sets of dyeing have been repeated using other ***set pH profiles*** with same initial and final pH values (i.e. Quadratic, Exponential and Ramp and the dyeing results have been measured and recorded for comparison as shown in Table 7.1

L*, a* and b* is an indication of the degree of lightness, redness-greenness and yellowness-blueness of the dyed sample. DL* expresses the degree of lightness difference between the batch sample and the standard sample and %R is the percentage reflectance of the dyed samples. DE* is an expression of the colour difference between the batch sample and the standard sample. Using the CMC (2:1) Colour Difference Equation, DE* value of 1.0 denotes that two samples have perceptible but acceptable colour difference. DE* less than one means that the colour difference is acceptable and greater than one means that the two colours do not match. The batch sample could be lighter or darker than the standard sample.

A: Standard Dyed Samples Using Supplier's Linear Dosing Profile (Final pH 10.92) Without Fuzzy Controller

B: Batch Dyed Samples Using User-Defined pH Profile (Final pH 10.72) With Fuzzy Controller

C: Batch Dyed Samples Using User-Defined pH Profile (Final pH 10.92) With Fuzzy Controller

D: Batch Dyed Samples Using Quadratic pH Profile (Final pH 10.92) With Fuzzy Controller

E: Batch Dyed Samples Using Exponential pH Profile (Final pH 10.92) With Fuzzy Controller

F: Batch Dyed Samples Using Ramp pH Profile (Final pH 10.92) With Fuzzy Controller

Table 7.1 Results of Fabric Dyeing for Different pH Profiles

Samples	L*	a*	b*	DL*	%R	K/S Value	DE*	Shade Difference
A	49.30	59.03	-2.36	-	5.52	8.08	-	-
B	49.63	58.39	-3.71	0.33	5.95	7.43	0.84	Lighter
C	47.39	60.03	-1.70	-0.91	4.73	9.59	0.91	Darker
D	48.62	59.66	-2.06	-0.68	5.30	8.46	0.30	Darker
E	49.43	59.33	-2.78	0.13	5.68	7.83	0.25	Lighter
F	48.67	59.59	-2.57	-0.63	5.21	8.62	0.59	Darker

From the results of the pH profiles tested, there is no significant colour difference between the standard sample and the samples obtained when using the various pH profiles. In all cases the DE* values are less than one and this means that the standard and batch samples are visually the same.

The controller system did not improve the colour yield in a significant manner when using any of the selected pH profiles. However, with the controller, colour reproducibility is fairly consistent for any of the pH profiles used provided the starting and especially the final pH and other dyeing parameters are maintained. When the final pH value is not reached, as is the case with sample B where the final pH was 10.72 instead of 10.92, the colour yield was slightly lower than the standard.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

In this research project, control strategies based on fuzzy-logic have been designed and implemented on a laboratory jet dyeing machine, with the aim of controlling the dyebath pH and studying the performance of the controller for a variety of reference pH profiles. To meet these objectives, the following works have been successfully achieved:

1. Development of a control program written in C for
   - (i) Data acquisition of pH from the dyebath
   - (ii) Implementation of the fuzzy control algorithm for controlling the pH of the dyebath, according to the different preset profiles.
   - (iii) Activation of acid and alkali dosing pumps for adjusting the dyebath pH according to the preset pH profiles.
   - (iv) Displaying the process parameters of interest on line.

2. Selection of appropriate pH sensor, transmitter and dosing pumps for the automated system.

3. Selection of appropriate interface card so as to enable data to be acquired by the PC from the dyebath, and control signals to be sent from the PC towards the dyeing process.

4. Design and implementation of driver circuits, which would actuate dosing pumps according to the command signals from the fuzzy control software.

5. Development of a linearised model for the dyeing process so as to obtain initial guesses for the fuzzy control gains through simulation using Matlab™ and Simulink™ software packages.

6. Testing and tuning the controller so as to optimise the pH tracking performance of the system.

7. Modification of the fuzzy controller so that its gain can be adapted according to the value of the desired pH, thus further enhancing the tracking performance.

8. Experimentation of the implemented system on linear, quadratic, exponential and user-defined reference profiles.

9. Comparing the colour yield performances of the dyed fabrics for different set pH profiles

Initial tests performed on the implemented system show that the fuzzy controller is able to track pH reference profiles with small error, for set pH values below 9.0. Above this value the deviation between actual and desired pH values becomes significant. The fuzzy controller has further been improved so that its gain can adapt to the values of the set pH. The resulting controller has been tested and shown to have a much better tracking performance, compared to its non-adaptive counterpart. The most severe tracking errors have been observed when the reference profile has the steepest gradients, namely in the quadratic profile. Consequently, this profile has been used for fine-tuning the adaptive fuzzy controller, and it has been observed that the tracking performance is also improved for the linear, exponential and user-defined profiles, respectively.

From the dyeing performance point of view, the controller system did not significantly improve the colour yield of the dyed fabric when using any of the selected pH profiles compared to the supplier's recommended pH profile. However, the system could be used to track down pH profiles other than those tested and analyse the dyeing performance of the recipes until an optimum pH profile is found.

The controller system also allows for good colour reproducibility between dyed batches when using any of the pH profiles provided the starting and especially the final pH and other dyeing parameters are maintained.

In industry, there are a number of variable parameters which may affect the final pH of the dyebath; the quality of the water, the fibre quality and source, the nature of the auxiliaries and the dyes could all play a major role in determining the final dyebath pH. pH is one of the most critical parameter in the dyeing of cotton with reactive dyes and the controller helps the dyer to monitor the performances of the both the process and the machine during dyeing as the pH is monitored in real time.

8.2 Recommendations for Further Work

1. Although the tracking error of the fuzzy controller has been significantly improved with the adaptive scheme, further improvement of its performance can still be achieved by adapting the controller input gain, k_e, continuously with the set pH value from the initial to the final pH values. Further experimentation is thus necessary to establish the relationship between the required controller gain and the reference pH.

2. The effect of the output gain, k_u, of the fuzzy controller on the tracking error can also be investigated so that both k_e and k_u can be varied continuously on line to minimise the tracking error.

3. Another possibility could be, instead of using two different concentrations, to modify the fuzzy controller in order to take into account the concentration of the chemicals. This can be done by including a third input to the controller, which is the actual pH of the plant. A different rule base will thus be generated. The action to be taken when the pH is within pH 7 and 9 will be different from the action to be taken in a pH range greater than 9, for the same error and change in error.

4. A fuzzy Self Organising Controller (SOC) can also be designed, whereby the controller gains remain unchanged, but the amount by which the fuzzy controller output changes, is updated continuously, according to changes in acid/ alkali concentration, or changes in the set pH values. A fuzzy SOC is also well suited for systems with characteristic time delays, like in the present application.

5. The system is very sensitive in the pH range of 7 to 9. A small amount of 100% NaOH causes sudden pH change. The high concentration chemicals used in the project make the pH control quite difficult. This difficulty may be overcome by using two different concentrations. A weak chemical concentration for the pH

range of 7 to 9 and a strong chemical concentration for a pH range of 9 to 11 may be used. However, this implies the connection of a third dosing pump to the system and modifications in the actual program codes.

6. The liquor circulation system of the plant is relatively large and therefore, the pH may not be the same throughout at the time of sampling. Additional sensors may be placed inside the bath. The average measured values can be computed so that more accurate readings are obtained.

7. A graphical user interface (GUI) can be developed to display graphs of actual temperature and pH. The dyeing parameters reference graphs can also be displayed if available. GUI software, such as Visual C++ and Visual Basic may be used for this purpose.

8. Repeated use of the pH sensor may cause certain dyes and chemicals to deposit on the latter. In the long term, the accuracy of the instrument may be impaired. It is therefore necessary to periodically remove, clean and recalibrate the sensor for reliable pH measurements. A method for cleaning and calibrating the sensor without the need to remove it from the dyeing machine could be identified. This could enable considerable savings in time and labour.

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